Energy Efficiency can help faster future Economic Growth in Greece

Scenario planning for 2030

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

I want to devote this work to my family, for their unconditional support, and to those friends, that made these past two years a journey to remember.

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Abstract

The present study was set to investigate two matters. One was the correlation between useful exergy and economic growth. The second was whether the faster recovery of the Greek economy by 2030 is possible through improving the country's aggregate exergy efficiency. To do that, first Greece's economy sectors exergy analysis was performed by implementing the Useful Exergy Accounting Methodology. The most important energy carriers (oil and electricity), useful exergy categories (mechanical drive and heat) and exergy intensive sectors were identified. It was shown that, there is a relatively stable relationship between useful exergy and GDP for the past three decades. Then, two extreme scenarios were formulated, assuming each, the pessimistic and optimistic developments of the labor, capital stock and exergy efficiency factors. Improvements in efficiencies were achieved, by implementing measures in the important sectors, which led to technology upgrades, and shifting from less to more efficient energy carriers (e.g. oil to electricity) and technologies (e.g. conventional burners to CHP). The economic model, which was used to forecast the future economic growth, links aggregate exergy efficiency and total factor productivity, and is based on the three factors of labor, capital and exergy efficiency. The outcomes of the two scenarios differed significantly, which proves that higher progress in the exergy efficiency of primary sectors can help economy grow more rapidly. Projections for useful and final exergy were made, based on the findings for useful work intensity and aggregate exergy efficiency, and they seem to increase, following economic growth.

Keywords

economic growth; Greece; exergy; energy efficiency; total factor productivity; useful work

Resumo

O presente estudo investigou dois assuntos. Uma delas foi a correlação entre exergia útil e crescimento econômico. A segunda foi se a recuperação mais rápida da economia grega até 2030 é possível através da melhoria da eficiência exergética agregada do país. Para fazer isso, primeiro foi realizado um análise de exergia dos setores da economia da Grécia com a implementação da metodologia de contabilidade de exergia útil. Os principais transportadores de energia (petróleo e eletricidade), categorias exergéticas úteis (acionamento mecânico e calor) e setores intensivos em exergia foram identificados. Foi demonstrado que existe uma relação relativamente estável entre exergia útil e PIB nas últimas três décadas. Em seguida, dois cenários extremos foram formulados, assumindo cada um, os desenvolvimentos pessimistas e otimistas dos fatores do trabalho, estoque de capital e eficiência exergética. Melhorias na eficiência foram alcançadas, através da implementação de medidas nos setores importantes, que levaram a atualizações tecnológicas e mudança para transportadores de energia (por exemplo, óleo para eletricidade) e tecnologias (por exemplo, queimadores convencionais para CHP) mais eficientes. O modelo econômico, utilizado para prever o crescimento econômico futuro, vincula a eficiência exergética agregada à produtividade total dos fatores e baseia-se nos três fatores do trabalho, capital e eficiência exergética. Os resultados dos dois cenários diferiram significativamente, o que prova que um maior progresso na eficiência exergética dos setores primários pode ajudar á economia a crescer mais rapidamente. Projeções para exergia útil e final foram feitas, com base nas descobertas de intensidade de trabalho útil e eficiência exergética agregada, e parecem aumentar após o crescimento econômico.

Palavras-chave

crescimento econômico; Grécia; exergia; eficiência energética; Fator total de produtividade; trabalho útil

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List of Acronyms

Agg.Eff.	Aggregate final-to-useful exergy efficiency
AMECO	Annual Macro-economic database of the European Commission
BaU	Business as Usual
CFC	Consumption of Fixed Capital
CHP	Combined Heat and Power
COP	Coefficient of Performance
CRES	Centre of Renewable Energy Sources
ECB	European Central Bank
EC	European Commission
ecp	Energy carrier’s product
EEE	Enhanced energy efficiency
ef	Energy flow
EIOU	Energy industry own use
ERDF	European Reginal Development Fund
es	Energy sector
ETS	Emission Trading System
EU	European Union
EV	Electric Vehicle
FEx	Final Exergy
GDP	Gross Domestic Product
GFCF	Gross Fixed Capital Formation
GHG	Greenhouse Gas
HTH	High Temperature Heat
IEA	International Energy Agency
IMF	International Monetary Fund
LDSA	Laboratory of Demographic and Social Analyses
LTH	Low Temperature Heat
LPG	Liquefied Petroleum Gas
MD	Mechanical Drive
Meta	Metamorphosis
MS	Member State
MTH	Medium Temperature Heat
NG	Natural Gas
NREAP	National Renewable Energy Action Plan

PIM	Perpetual Inventory Method
PWT	Penn World Table
RES	Renewable Energy Sources
SEV	Hellenic Federation of Enterprises
SMEs	Small and Medium-sized enterprises
SNA	System of National Accounts
TFP	Total Factor Productivity
UEAM	Useful Exergy Accounting Methodology
UN	United Nations
UW	Useful Work
WWF	World Wide Fund for Nature
YPEKA	Ministry of Environment and Energy, Greece

List of Symbols

A_t	Total factor productivity
e_i	Daily metabolizable content of feed intake [kcal/d]
e_m	Daily metabolizable energy content of supplied food per capita [kcal/d]
h	Heads of animals [-]
i_t	Investment as percentage of previous year’s GDP in year t [-]
K	Capital
L	Labor
p	Population [-]
r	Compression ratio [-]
T_o	Environmental Temperature [K]
T_s	Service Temperature [K]
t	Fraction of a day devoted to work [-]
Y_t	Gross domestic product
α_i	Deviation form ideal process coefficient
α_K	Capital share [-]
α_L	Labor share [-]
α_y	Intake to end use ratio in year y [-]
γ	Specific heat ratio [-]
δ_t	Depreciation rate of fixed capital in year t [-]
ε_{ag}	Aggregate final-to-useful exergy efficiency [-]
ε	Second law efficiency [-]
η	First law efficiency [-] or Luminous efficacy [lm/W]
φ_i	Exergy factor [-]

Chapter 1

Introduction

In this first chapter of the thesis a short introduction of the project is given. Initially the link in theory between exergy and economic growth is briefly presented and an overview on current research in mentioned. Then the motivation for selecting the present topic is explained and its outlook is defined. Finally, the outline of the thesis is presented.

1.1 Overview

In the world we live, whether it is a civilised society or outdoors nature, every activity we can observe is enabled by energy. From a taxi moving through the city or an elevator lifting people between floors to a squirrel climbing up a tree, each of these actions in their environment is happening, because the subject has available ‘fuel’ to do so. According to the first law of thermodynamics, inside a closed system the total energy is always conserved when any transformation process is taking place. A part of it will be the useful energy output while the rest will convert to low-temperature waste heat and their sum will equal the input energy. The energy efficiency, or first law efficiency, is used to demonstrate the cost-benefit relation of a conversion process in energy terms. Namely, it gives the ratio of the useful energy output to the total energy input of this process. However, this measure of efficiency shows limitations, since first, some applications, such as the heat pump, can potentially have energy efficiency higher than 100%, and second, this measure does not illustrate to what extend the quality of energy is affected during the process, e.g. converting entirely electrical energy to heat with an electric heater.

To define a more precise efficiency of a process, first the thermodynamic concept of *exergy* is introduced, which is the capacity of energy to do mechanical work. More explicitly, exergy corresponds to the part of an energy flow, which can produce useful work after every consecutive transformation process, yet this fraction of energy is reduced in each step. On the other hand, the non-useful part, that is created from the irreversible destruction of exergy, relates to the process of entropy creation. Exergy is defined relative to the contrast between the thermodynamic system of interest and its environment, meaning the bigger the differences they have in terms of temperature or potentials, i.e. gravitational/electrical/chemical, the higher the exergy of the system. Concluding, the exergy efficiency, or second law efficiency, is the ratio of the minimum energy input to the actual energy input of a process, or in exergy terms, the ratio of the exergy output and the exergy input. This means that the minimum theoretical exergy requirement of a system corresponds to the best possible performance.

In the early 1950s, to measure the size of a country’s economy in terms of GDP, an aggregate production function of *capital* and *labor services* was introduced. This allowed economists to consider the relative importance of the two factors of production and sources of productivity growth. Eventually though, Solow [1] discovered that considering as relative factors only capital and labor, they could not account for the entire observed growth in the US GDP. This difference, between the estimation of the function and the measured GDP, was identified by some as the ‘Solow residual’, which is a qualitative ‘neutral’ time-dependent multiplier of the labor-capital combination and is linked with the increase in total factor productivity (TFP). This TFP is an exogenous factor, that has also been tried to be explained by technological progress, yet, it cannot be quantified. A new aggregate production function, including the TFP multiplier, called the Solow-Swan model has been established since and is widely used to estimate GDPs. Nevertheless, not all economists have been happy with the use of production functions because they show limitations, like in their capacity to measure sustainable growth, wealth distribution, fuel sources etc. [2]. Furthermore, the role of energy is thought to be minimal in mainstream economics.

Another point of view, given by ecological economists, suggests that human development and economic progress are strongly correlated to exergy. This idea relates to the ability, to progressively utilize higher quality forms of energy in the numerous productive processes and energy services, as well as to the fact that an ongoing process requires a continuing flow of exergy to stay active. Equipment without an enabling exergy flow would be inert and unproductive [2]. Past research (e.g. [3]) has shown correlation between the useful work injected in the US economy and its growth. Furthermore, another study tries to explain the TFP in Portugal with the help of the aggregate second-law efficiency of the Portuguese system [4]. This means that, besides the available capital existing inside a country and the labor hours devoted for production, the third factor could also be qualitatively explained by considering the useful exergy generated and the technology utilized to do it. For the purpose of exergy analysis in country-scale, the methodology of Useful Exergy Accounting (UEAM) was developed by Ayres and Warr et al. [3], [5].

1.2 Motivation and contents

The country of Greece locates in the southeast corner of Europe and has a relatively small economy compared to most of its EU neighbors. In the past the development of the country has been far from constant, showing different growing behaviors, with periods of stagnation on one side or rapid economic progress on the other. This unstable course, along with other signs, might have been indications of an unsustainable growth. Yet, radical changes to alter the way progress was made were never a priority. Eventually, the country's economy went through a big shock after the financial crisis of 2007-2008, which led it to lose a quarter of its GDP only in a few years. This phenomenon has been characterized by many as the biggest crisis after the Great Depression. Today, a decade after the fall, three bailout programmes later and a national debt higher than ever before, the county's economy is trying to stand again on its own feet.

This thesis has two main objectives. The first is to investigate the relationship between useful exergy and economic growth in Greece. The second is to examine how changes in the present energy system could contribute towards the faster recovery of the Greek economy, through potential suggested policies and implemented measures. In order to do that, initially exergy data and economic figures of the country will be analyzed and past trends will be revealed. This will help explore the relation between useful exergy and economy. Then, two main scenarios will be created, focusing mainly on energy savings, through changes in the energy mix and technological efficiencies' improvement. One will assume that, progress continues on the path that is already carved, which is expected to lead to mild development. The other will consider stronger adjustments that will eventually lead to better aggregate second-law efficiency, consequently to higher TFP, and in that manner, growth will be boosted. Ultimately, the results will be evaluated and discussed in terms of projected GDP as well as exergy.

This thesis is composed of 5 main chapters. The outline is as follows:

- Chapter 1 - Introduction

- Chapter 2 - Literature review and past trends:
  This chapter provides the theoretical basis for the thesis and presents figures related to the past exergy trends and economy of Greece. The links between useful exergy and economic growth is explained and explored and an alternative model for making GDP forecasts is given.

- Chapter 3 - Scenario development for Greece up to 2030:
  In this section, one pessimistic and one optimistic scenario are created for the future development of each of the three factors of labor, capital and aggregate exergy efficiency. The purpose is to combine these factors in two main scenarios and later use them for economic growth estimates.

- Chapter 4 - Final projections:
  In this part, the projections of economic growth are made, based on the previously formed main scenarios. Useful and final exergy projections follow. The results are discussed.

- Chapter 5 - Conclusions:
  In this final chapter, the aim of the thesis and the process followed are recapped. The main points concluded are presented collectively. Recommendations for further research are given.

Chapter 2

Literature Review & Past trends

The purpose of this chapter is to provide and explain the theorical basis of the current thesis, display past trends related to Greece's exergy analysis and economy figures and investigate if there is a relation between the production of useful work and economic growth. Initially, the concept of exergy will be introduced and the methodology to calculate the useful work produced in an economy will be analyzed. Following, related exergy trends will be shown and the aggregate exergy efficiency for Greece will be estimated. Then, the neoclassic approach of a country's economic growth will be presented. This will be followed by a brief historic trajectory and the relevant economic figures of Greece. Next, the relation between useful work and economy will be examined. Finally, the concept of aggregate exergy efficiency will be linked to economic growth, and based on this, an alternative model to make country-scale scenarios will be given.

2.1 Exergy analysis

While the first law of thermodynamics says that, in a closed system when a transformation process takes place, the total energy is conserved, the second law of thermodynamics declares that all spontaneous processes are irreversible. Namely, the total energy that can be transformed into work is reduced in every consecutive step of each transformation process. The fraction that remains with the potential to produce work is the exergy, while the part that is not useful anymore corresponds to entropy [2], [4], [6].

Additionally, exergy can be defined by the contrast between the thermodynamic system of interest and its environment, meaning the bigger the differences they have in terms of temperature or potentials i.e. gravitational/electrical/chemical, the higher the exergy of the system. For example, in a hydro power plant, if the water level at the two sides of the dam is the same, then there is no gravitational potential energy. So, even though there is available energy on both sides, the exergy of the system is zero, meaning that no work can be made by the turbines, because the water will not flow from one side to the other, producing electricity. However, if the dam's upstream water level is higher than in downstream, there is gravitational potential energy available, and consequently, exergy is available as well because work can be made [2], [6].

The different forms and stages in which exergy can be found vary across a transformation process spectrum. Early on, it exists in its raw form inside natural resources like solar radiation and biomass, which are renewable, or like coal and minerals which are considered finite. This is the primary stage. Then, as these resources are harvested and transformed, e.g. extracting crude oil and refining it in benzine, the exergy is available to be used, which is the finale stage of the process. Finally, exergy reaches its end use, being the outcome delivered as work, and it is in its useful stage, e.g. the exergy that effectively was used for the motion of a vehicle.

To sum up, throughout the energy flow process, where extraction, transformation and consumption of energy (resources) happens, three stages can be identified: primary, final and useful.

In a broader outlook, the different forms and stages of exergy can be identified for the entire structure of a country's economy, in order to put special focus on the useful work generated. In the present case, the country addressed is Greece and its exergy analysis will be done using the Useful Work Accounting Methodology, following the work of Ayres and Warr et. al [3]. This methodology has four steps, applied to all energy carriers' annual values. More specifically these steps include:

1. Final energy to *final exergy* data conversion.
2. Allocation of the final exergy consumption to *useful work categories*, for each final use sector.
3. *Second-law efficiencies* estimation for every final-to-useful exergy transformation.
4. Sum of all *useful work* values to a total value for each useful work category.

The energy data needed for the calculation were made available by the International Energy Agency (IEA) World Energy Statistics [7], which provides systematic information on energy for a national scale worldwide, from 1960 to 2014. The advantage of this collective data source is to avoid possible inconsistencies and variations that may be found when comparing different countries' own national statistics on energy accounting and sectoral disaggregation. The calculation sequence followed is similar to the ones described in [5], [8], [9].

2.1.1 Final energy to final exergy data conversion

Exergy can be defined as the maximum amount of work that can be obtained by a system as it approaches thermodynamic equilibrium with its surroundings through a sequence of reversible processes [3], [10]. Calculating exergy from energy values depends on the capacity that different energy forms have in order to deliver work. In energy calculation, energy is usually displayed in the forms of: fuel, electricity, mechanical work, heat and non-energy products, having each of them a different exergy content [5].

The flows of mechanical (potential and kinetic) and electric energy can theoretically be completely converted to work, therefore their exergy factor is assumed to be 1. However, in the case of heat the energy flow cannot be entirely converted to work. The maximum extractable work from a system connected to a thermal reservoir at T_0 is the work that can be obtained by an ideal Carnot engine. Thus, for heat the exergy factor is less than 1 [8]. The heat of combustion (enthalpy) of a fuel is nearly equivalent to its exergy content. There is a slight difference related to heat which is lost in the vaporization of water (low heating value) and work which is produced 'on' the atmosphere by the dissipation of the products of the combustion.

Moreover, in the present case, the energy inputs for the conversion into exergy go beyond the conventional energy accounting statistics, considering: food and feed for humans and working animals, respectively, for muscle work, as well as and non-conventional sources like wind and water streams for use in boats, mills and wells, for mechanical drive.

2.1.1.1 Energy Industry own use, Industry, Transport and Other sectors

In the energy statistics database [7], data were provided disaggregated by 68 products (of natural resources) of final energy, and these data are disaggregated for the main economic sectors. These products were grouped in 10 sets of energy carriers according to their origin [5], [8]. As a result, a list of these main energy carriers was created along with their exergy factors and can be seen in Table 1. More analytically, the products included in each of each carrier can be found in Annex Table 1.

In order to estimate the final exergy consumed in Greece throughout the years, the energy data of the main energy sectors of economy were taken under consideration. These are: 1. Energy industry own use (EIOU), 2. Industry, 3. Transport, 4. Other (including the residential and services sector) and finally the 5. Food and Feed. The energy data are given, within each sector, disaggregated by sub-sectors (or as in IEA, “flows”) and origin (the mentioned products), as in Annex Table 2. As mentioned, the IEA database provides time series from 1960 to 2014, for each sector.

Table 1: Energy Vectors with their exergy factors.

Energy vectors	Exergy factors (φi)
Coal and Coal Products	1.06
Oil and Oil Products	1.06
Coke	1.05
Natural gas	1.04
Combustible renewables	1.11
Electricity	1
Food and Feed	1
CHP and geothermal heat	0.4
Solar thermal heat	0.25
Other non-conventional	1

In their raw form all the energy carrier products’ values are given in different units of either kilotonnes (kt), Terajoules (TJ) or Gigawatthours (GWh). Thus, the first step was to convert the values at a common and desirable unit, in this case to TJ. This was done with the help of an additional dataset of the IEA database which provided the average net calorific values of each energy carriers’ product in KJ/kg. The outcome is a new database with the final energy values of each energy carrier in TJ, from 1960 to 2014.

In the process, the new data are multiplied using eq. (1) where for each year y, $FEx_{ecp,y}$ is the final exergy of each energy carrier’s product ecp, $FEn_{ecp,y}$ is the final energy of each energy carrier’s product and, φ_i the respective exergy factor from Table 1, used according to A.1. The result is a new final exergy database disaggregated by energy carriers’ products, from 1960 to 2014.

The sum per year, given by eq. (2), of all the final exergy values disaggregated by energy carrier product, $FEx_{ecp,y}$, and flows, ef, gives the annual final exergy $FEx_{ef,y}$ of each flow. Consequently, the sum of the flow’s final exergy, according to Annex Table 2 and as in using eq. (3), gives the annual final exergy of each energy sector $FEx_{es,y}$, where the number of flows n is different for every sector.

$$FEx_{ecp,y} = FEn_{ecp.y} * \varphi_i \qquad (1)$$

$$FEx_{ef,y} = \sum_{ec=1}^{68} FEx_{ecp,y} \qquad (2)$$

$$FEx_{es,y} = \sum_{ef=1}^{n} FEx_{ef,y} \qquad (3)$$

2.1.1.2 Food and Feed

For the of Food and Feed sector, the data for the population of Greece were taken from [11] and the food intake data were found in [12]. Working animal heads' data were taken from [13] and the feed intake from [14], [5].

In the case of humans, final exergy is estimated using eq. (4) where for year y, $e_{m,y}$ stands for the daily metabolizable energy content of supplied food *per capita*, p_y, is the population and 1.23 is the gross to metabolizable ratio [8], [15]. For working animals, the final exergy is estimated by eq. (5). In the equation, e_i is the daily metabolizable energy content of feed intake, estimated by Serrenho et. al [5] and Henriques, S. [14], as 12,198 kcal/d for asses, 18,742 kcal/d for horses and 15,832 kcal/d for mules. The heads are noted as h_i in the equation, the gross to metabolizable ratio is considered as 1.54, while α_y is the *supplied to eaten* ratio and equal to 0.64 [8], [15].

$$FEx_{food,y} = 365 e_{m,y} p_y 1.23 \tag{4}$$

$$FEx_{feed,y} = 365 h_{i,y} e_i 1.54 \frac{1}{a_y} \tag{5}$$

2.1.1.3 Final exergy

The final exergy of each energy sector as well as the total final exergy of Greece are displayed in Figure 1, while the sector's shares of the total are shown in Figure 2.

In Figure 1, from 1960 to 2007 the total final exergy used in Greece increased about 4.5 times - from around 188000 TJ to 1086000 TJ. Then, after the financial crisis of 2007-2008, this value started dropping, reaching 795000 TJ in 2014.

Regarding food, there is a mild constant increase throughout the entire time series, following the same development of the population (Annex Figure 1). However, final exergy related to feed seems to have decreased significantly its relevance within the country's consumption (Figure 2) from 1960, when its share surpassed 30% of the country's total final exergy, to 2014 when its share had already dropped to less than 5%. As this decrease is similar to logarithmic decrease in the mentioned period, the feed final exergy has evolved similarly to the decreasing populations of working animals throughout the years (Annex Figure 2). This trend could be explained by the decreasing need of animals as workforce in the economy.

Energy Industry own use of final exergy has increased throughout the timespan studied. It started with the lowest consumption values in the 1960s and 1970s, increasing gradually up until the beginning of the 2000s, when it reaches similar values to food's final exergy, staying relatively constant ever since, around 80000 TJ.

Industry and Other sectors' final exergy totals were practically equal in 1960 and followed similar trends until the mid 1970s. Then, Industry's final exergy continued increasing, reaching as high as 200000 TJ in the early 2000s, before dropping significantly, down to around 136000 TJ in 2014. As for the Other sector, from the mid 1980s it follows a similar trend to the Transports' sector, consuming each around 25% in the 1980s and around 35% in the late 2000s. The later, Transports, had a gradual increase from the 1960s, with a share of 18% up until 2014 (32%of Greece's final exergy consumption). Both the Transports and Other sectors, like Industry, had a significant drop after the second half of the 2000s.

Regarding the final exergy related to food and feed, it accounted for more than 50% in 1960, since Greece's industry had not yet developed and the production relied on the physical work of people and animals for agriculture. This share has dropped to less than 10% in the recent years. Opposite to that, the final exergy injected in Industries, transport and other sectors increased dramatically throughout the year with the industrialization of the country.

Still, the biggest shares of final exergy nowadays are used in transportation and other sectors because of the continuous grow in welfare and service provision, with a combined share ranging between 60% and 70% of the total. This is while the share of the industry started falling after 1980 due to the lack of emphasis from Greece's governments in growing its industry and increasing its production of goods proportionally to its economic development.

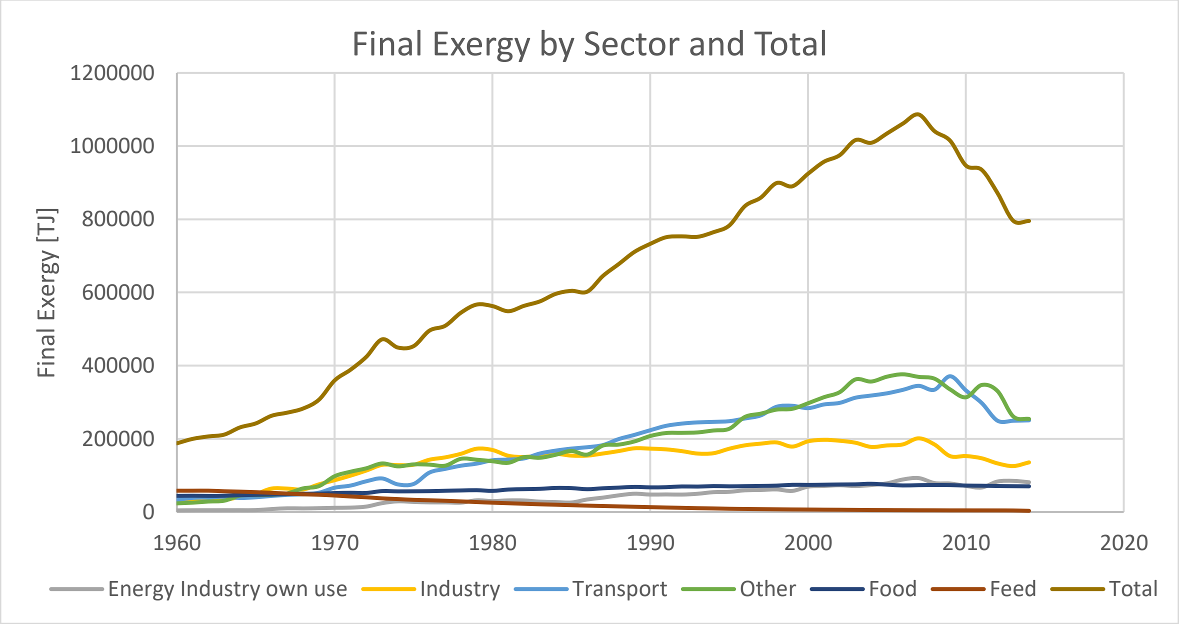

Figure 1: Final exergy by sector and total for Greece, 1960-2014.

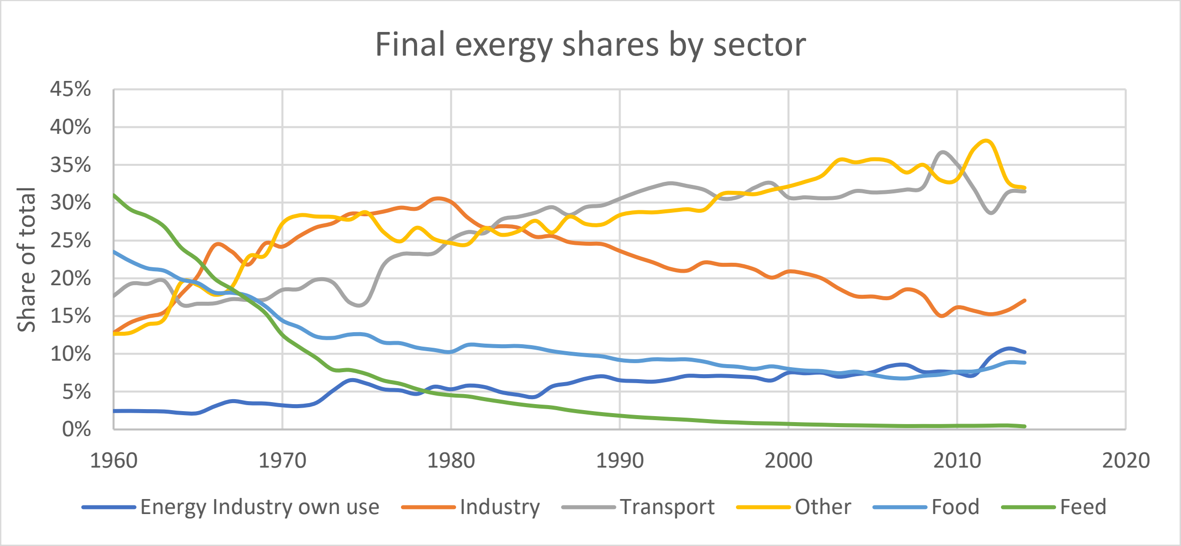

Figure 2: Final exergy shares for Greece 1960-2014.

From another point of view, Figure 3 shows final exergy disaggregated by energy carriers' contribution. It is clear that oil is the energy carrier primarily used in the country, starting at 70500 TJ in 1960 and increasing up to about 669000 TJ in 2006, after which the consumption fell sharply until it reached almost 417000 TJ in 2014. This drop could be partly explained by the increase in fuel prices in the country after the financial crisis. Comparing this trend with the one of GDP (presented later in Figure 9) it is safe to assume that oil has been the principal driver of the economy.

The second most important energy carrier is electricity, thought with much lower values, with 7250 TJ in 1960 and increasing almost linearly to 231500 TJ, in 2008. Since then it started falling mildly, however not as steeply as the drop rate of oil. This difference might be explained by the country's low electrification level and, thus, lower dependence on electricity.

Combustible renewables are increasing mildly the last decades, with low values around 50000TJ. Finally, it is meaningful to point out that coal started diminishing after 2000, while their part seems to be substituted by natural gas.

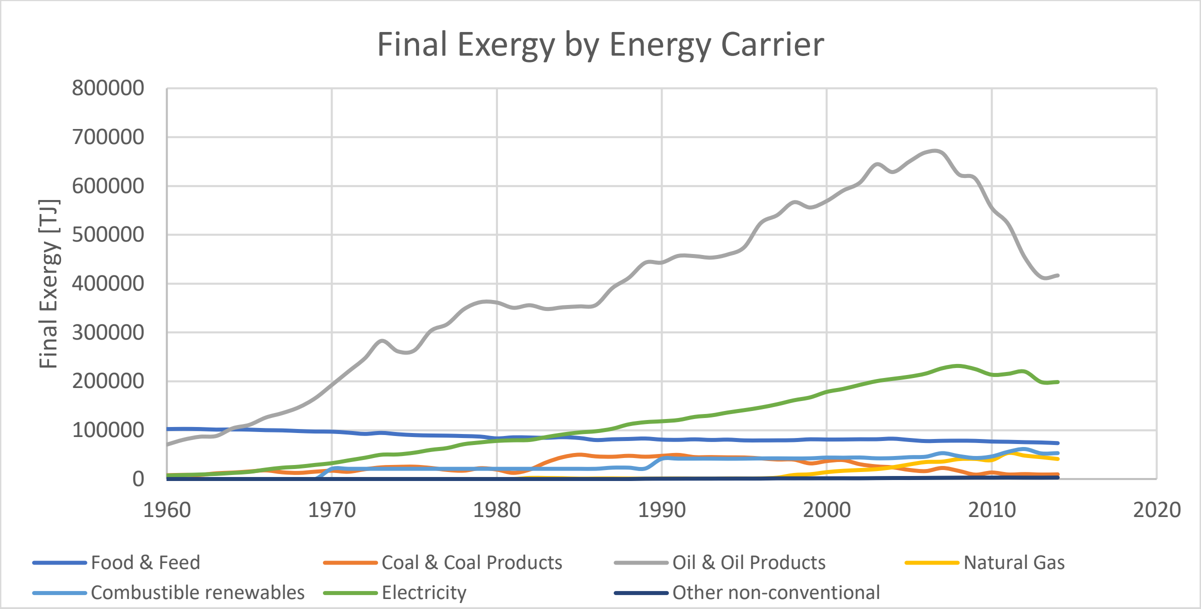

Figure 3: Final exergy by energy carrier in Greece, 1960-2014.

2.1.2 Allocation of the final exergy consumption to useful work categories

Final exergy consumption is allocated in five main useful work categories: Heat, Mechanical drive, Light, Other electric uses and Muscle work [5], [8], [9]. Non-energy uses are not taken into consideration.

The Heat category concerns all heat used by processes and devices in the economy and can be divided in three sub-categories: high temperature heat (HTH) (>500 °C) for heat-intensive industry processes like iron, cement, oil refining; medium temperature heat (MTH) (120-500 °C) used as process heat in the majority of industrial sectors such as metallurgical, chemical and energy industry processes; and, also, low temperature heat (LTH) (<120 °C) for processes related to residential and industrial hot water, cooking, space heating and other industrial low temperature processes. This last heat sub-category can be divided further in more classes since second-law efficiencies are more sensitive to lower temperatures [8], [9].

The mechanical drive category consists of mechanical work related to drive and movement by a mechanical device, indifferent of the carrier of final exergy. Due to different energy sources (fuels) having different second-law efficiencies, subcategories of mechanical drive are considered instead of using an estimation of aggregate efficiency for the whole category. Common uses in the category are internal combustion engines (diesel, gasoline, natural gas) and electric engines. A main subdivision of mechanical drive uses is whether they are to transport (mobile) or stationary [8], [9].

Light considers all lighting for residential, services and industrial uses by any energy carrier, e.g. electricity in modern societies and oil products in developing economies [9].

Other electric uses are electrical appliances not included in the previous categories, mostly used for communication, electronic and electric devices and electrochemical processes [8], [9].

Finally, muscle work refers to food and feed’s exergy that is converted into actual mechanical work by humans and animals, respectively [8], [9].

This allocation is based on the mapping for energy end-uses made by IEA, acquired from the supplementary data of Serrenho et. al [5]. These end-uses and respective useful work categories are listed in Table 2.

Table 2: Disaggregation of end uses by useful work category

Useful work category	End-use
High temperature heat	Fuel-HTH (500 °C)
Medium temperature heat	Fuel-MTH (150 °C); CHP-MTH (150 °C)
Low temperature heat	Fuel-LTH (120, 90, 50 °C); CHP-LTH (120, 90, 50 °C); Electricity-Industry LTH (120 °C); Electricity-Other sectors LTH (50 °C)
Mechanical Drive	Steam locomotive; Coal-Stationary Mech. Drive; Oil-Stationary Mech. Drive; Diesel vehicles; Gasoline/LPG vehicles; Natural gas vehicles; Aviation; Navigation; Diesel-electric; Electricity (Industry; Transport; Other sectors)-Mechanical drive
Light	Coal/Oil light; Electricity-Industry light; Electricity-Other sectors light
Other electric uses	Electricity-Industry other electric uses; Electricity-Other sectors other electric uses
Muscle work	Food; Feed

2.1.3 Second-law efficiencies estimation

There are two different efficiency definitions that are often used in thermodynamics [8], [16]–[18]. One is the energy efficiency or first-law efficiency and the other is the exergy efficiency or second-law efficiency.

The energy efficiency is expressed as the fraction of energy of desired kind that is transferred in a process [16] , as in eq. (6). For example, when examining a power cycle, the division of the net work done by it with the heat input into the cycle, is the first-law efficiency. Consequently, because of the first and second law of thermodynamics for this case the result is $0 \leq \eta \leq 1$. However, this energy efficiency behaves differently for some energy uses and devices, e.g. heat pumps efficiencies can be perceived to reach higher than 1, if COP is considered as their measure of efficiency, since the relevant energy input does not consider also the heat provided from the environment (cold reservoir). Thus, the first-law efficiency does not provide a comparable figure of quality across energy uses [8], [16].

The exergy efficiency is defined as the ratio of end use/source in exergy terms [19], as in eq. (7). This kind of efficiency is widely accepted and used as a figure of merit for energy uses, since for each process it scopes the distance from the theoretical ideal process, by comparing the theoretical maximum with the actual amount of work output. Because of the second thermodynamics’ law, the second-law efficiency is restrained to be 0≤ε≤1 and as a result, for a given energy use, resembles a figure of closeness and quality towards an ideal process.

$$\eta = \frac{desired\ energy\ transfer}{relevant\ energy\ input} \qquad (\ 6)$$

$$\varepsilon = \frac{desired\ exergy\ output}{relevant\ exergy\ input} \qquad (\ 7)$$

In order to obtain second-law efficiency values, the following definition is used, by applying the definition of exergy to eq. (7) [8],

$$\varepsilon = \frac{minimum\ amount\ of\ work\ required\ to\ produce\ the\ desired\ energy\ output}{maximum\ amount\ of\ work\ that\ could\ be\ produced\ from\ the\ relevant\ energy\ input} \qquad (\ 8)$$

Coal, oil, natural gas combustible renewables and heat

This subsection is relevant to all energy carriers whose final energy values are obtained through IEA energy balances, besides electricity (defined afterwards). Second-law efficiencies are determined for every disaggregated end use category (Table 2) and year. The categories correspond to heat, mechanical drive and lighting uses.

2.1.3.1 Heat

The second-law efficiencies (ε) for heating are functions of technological first-law efficiencies (η) and of environment (T_0) and service temperatures (T_s) [16], [5]:

$$\varepsilon = \eta(1 - \frac{T_0}{T_s}) \qquad (\ 9)$$

For different heating categories, corresponding first-law efficiencies were taken from Serrenho [5], based on the evolution of technology [20]. The ranges of these first-law efficiencies as well as the respective service temperatures for each heating category, are displayed in Table 3.

Table 3: Temperatures and first-law efficiencies for each heating category [20], [17], [5].

Heating Category	Service temperature (T_s)	First-law efficiency (1960-2009)
Fuel – high temp. heat (500 °C)	500 °C	58% - 71%
Fuel – medium temp. heat (150 °C)	150 °C	
Fuel – low temp. heat (120 °C)	120 °C	
Fuel – low temp. heat (90 °C)	90 °C	
Fuel – low temp. heat (50 °C)	50 °C	49% - 57%
CHP – high temp. heat (150 °C)	150 °C	58% - 71%
CHP – low temp. heat (150 °C)	120 °C	
CHP – low temp. heat (90 °C)	90 °C	
CHP – low temp. heat (50 °C)	50 °C	49% - 57%

The lowest temperature heat categories are typically referring to domestic heating, where less efficient, (in terms of first law efficiency) open chimney heaters are usually used and the service temperature is lower. These two factors lead to lower second law efficiencies than in the rest of the categories. Given by Serrenho in [5] and found in [21], the environmental temperatures for Greece where identified at 17.7°C for the annual average and 9.9°C for the winter average. Based on the assumption that space heating occurs only in winter months, the Low Temperature Heat (50 °C) second-law efficiency was taken as the average between low temperature heat uses efficiency (annual average temperature as the environment temperature) and space heating uses efficiency (winter months' annual average temperature as the environment temperature; December, January, February) [21].

Regarding the Combined Heat and Power (CHP) heating second law efficiencies, a similar approach was followed, using (10) and considering that CHP heat is delivered at 180 °C (T_1).

$$\varepsilon = \eta \frac{1-\frac{T_0}{T_s}}{1-\frac{T_0}{T_1}} \tag{10}$$

2.1.3.2 Mechanical Drive

The second-law efficiencies regarding mechanical drive[1] were taken from the supplementary data of [5] and are based on a variety of methods and literature. Moreover, based on the assumption that the countries of EU-15 had fairly access to equal technologies since 1960, Greece's second-law efficiencies are considered the same as for the rest of these countries according to Serrenho et. al [5]. For steam locomotives, efficiency estimations in [5] were adapted from Fouquet [20] and Smil [22] and then extrapolated in order to match estimations for recent years from Nakicemovic [23]. In the fields of navigation, aviation and oil- and coal-stationary mechanical drive, efficiencies were based on the work of and Ayres and Warr [2]. For diesel-electric technologies efficiencies are based on Nakicenovic, Gilli [23] and Ayres [24].

Second-law efficiencies for gasoline engines are estimated using eq. (11). The coefficients α_i, (found in Table 4) with $0 \leq \alpha_i \leq 1$, are the relation of real to ideal use settings and the $\eta_{theoretical\ maximum}$ (estimated using (12)) depends on the compression ratio (Annex Figure 3) and the specific heat ratio ($\gamma = C_p/C_v \approx 1.4$) [5].

---

[1] Note that as exergy is measure as the potential to do work, and as all work "can be converted" into work, the second law efficiencies for mechanical drive uses are, in fact, the same as the first law efficiencies – the machine efficiencies.

$$\varepsilon \approx \eta_{theoretical\ maximum} \prod_{i=1}^{6} \alpha_i \quad (11)$$

$$\eta_{theoretical\ maximum} = 1 - (\frac{1}{r})^{\gamma-1} \quad (12)$$

Table 4: Considered αi coefficients. Based on [5], [16], [25], [26].

Coefficient i	Meaning	Approximate value
1	Reduction due to stoichiometry deviations	0.75
2	Combustion and cylinder wall's losses	0.75
3	Friction losses	0.85-0.90
4	Partial load	0.40-0.45
5	Accessories losses (includes air conditioning)	0.90
6	Transmission losses	0.75 (autom.); 0.90 (manual)

In respect to diesel vehicles, the efficiencies are assumed to be 25% higher than for gasoline ones, since a diesel engine can achieve higher compression ratios and better fuel-burning efficiency [16].

2.1.3.3 Light

For all lighting efficiencies (coal/light and electric) an indirect procedure is used. The maximum luminous efficacy of a light, emitting at the wavelength for which the human eye is most sensitive (638lm/W), is taken as reference. Thus, the lighting efficiency of each light source is the distance to the maximum luminosity possible, in accordance with eq. (13) [24], [27], where η is the luminous efficacy of the light source. Annual estimation for average luminous efficacy in United Kingdom can be seen in Annex Figure 4, provided by [20] and is considered the same for Greece [5].

$$\varepsilon = \frac{\eta}{683 lm/W} \quad (13)$$

2.1.3.4 Electricity

In the case of electricity, useful work estimation is approached in another way by considering the different end-uses of electricity. The methodology applied in [5] for all EU-15 countries, is also followed in this work for Greece, where different shares of electricity end-uses are considered for industries, transports and the other sectors. Note that electricity is used for mechanical drive, heat, light and other electric uses in the industrial and the other sectors, while for transports it is considered that electricity is used entirely for mechanical drive. The series of shares are acquired from the work presented in [5] and are shown in Annex Figure 5 and Annex Figure 6 for Industries for Other sectors, respectively, where the sum of end-use shares each year is 100%.

Regarding the second-law efficiencies of the electricity end-uses, they were estimated using various methods by Serrenho et. al in [5] and were obtained and used unchanged from that work.

2.1.3.5 Muscle work (Food and Feed)

As far as muscle work is concerned, the corresponding useful exergy is not calculated as for other carriers with an exergy efficiency and final exergy totals. Instead, the useful work is estimated directly as described below.

On one hand, in the case of humans, muscle work is estimated using eq. (14) where for year *y*, $e_{m,y}$ stands for the daily metabolizable energy content of supplied food per capita [12], p_y stands for the population [11] and α_y is the intake to end-use ratio [8], [15]. For humans, this ratio ranges from 75% in 1960 to 63% in 2009. Moreover, *t* is the working fraction of the day considered, in this case as 8/24, by assuming a daily average of 8 hours of muscle work activity [15]. The ε is the food/feed-to-useful work efficiency and has the value of 13% for both humans and working animals [22].

On the other hand, in the case of working animals, the muscle work is estimated by eq. (15). In the equation, e_i is the daily metabolizable energy content of food intake and it has been estimated in [5] as 12,198 kcal/d, 18,742 kcal/d and 15,832 kcal/d for asses, horses and mules respectively[5], [14]. The heads h_i of working animals for Greece are provided by [13].

$$U_{MW_{h,y}} = 365 e_{m,y} p_y t a_y \varepsilon \tag{ 14}$$

$$U_{MW_{wa}} = 365 h_{i,y} e_i \varepsilon \tag{ 15}$$

2.1.3.6 Estimated Second-law efficiencies

Following the methods presented on the previous sub-chapters, as well as the findings in [5] showed above, the second-law efficiencies of all end-uses were found for the period of 1960-2009. From the last year of the series up to 2014, data were considered constant and equal to the values of 2009. This decision was taken to avoid resulting in further differences in efficiencies and, instead, emphasize the changes of useful exergy shares in this last part of the time series. The efficiencies are displayed in Figure 4.

As can be seen in the graph, the lowest exergy efficiencies are of uses: fuel-low temperature heat (LTH), light, steam locomotives, diesel, gasoline/LPG and natural gas vehicles, CHP-LTH (50 °C), heat from electricity and other electrical uses. The lower values of these end-uses start around 2.4% in 1960 and go as high as 18.5% in 2014.

Following, higher efficiencies than the mentioned are associated with the end-uses: fuel-medium temperature heat (MTH), coal- and oil- stationary mech. drive, aviation, navigation, and diesel-electric. Their lower values can start from circa 18.1% in 1960 and increase to approximately 40 % in 2014.

Finally, the highest efficiencies are for the end-uses: fuel-high temperature heat (HTH), CHP-MTH, CHP-LTH (90 °C, 120 °C) and mechanical drive from electricity. The values range from 36.2% in 1960 to 87.3% in 2014.

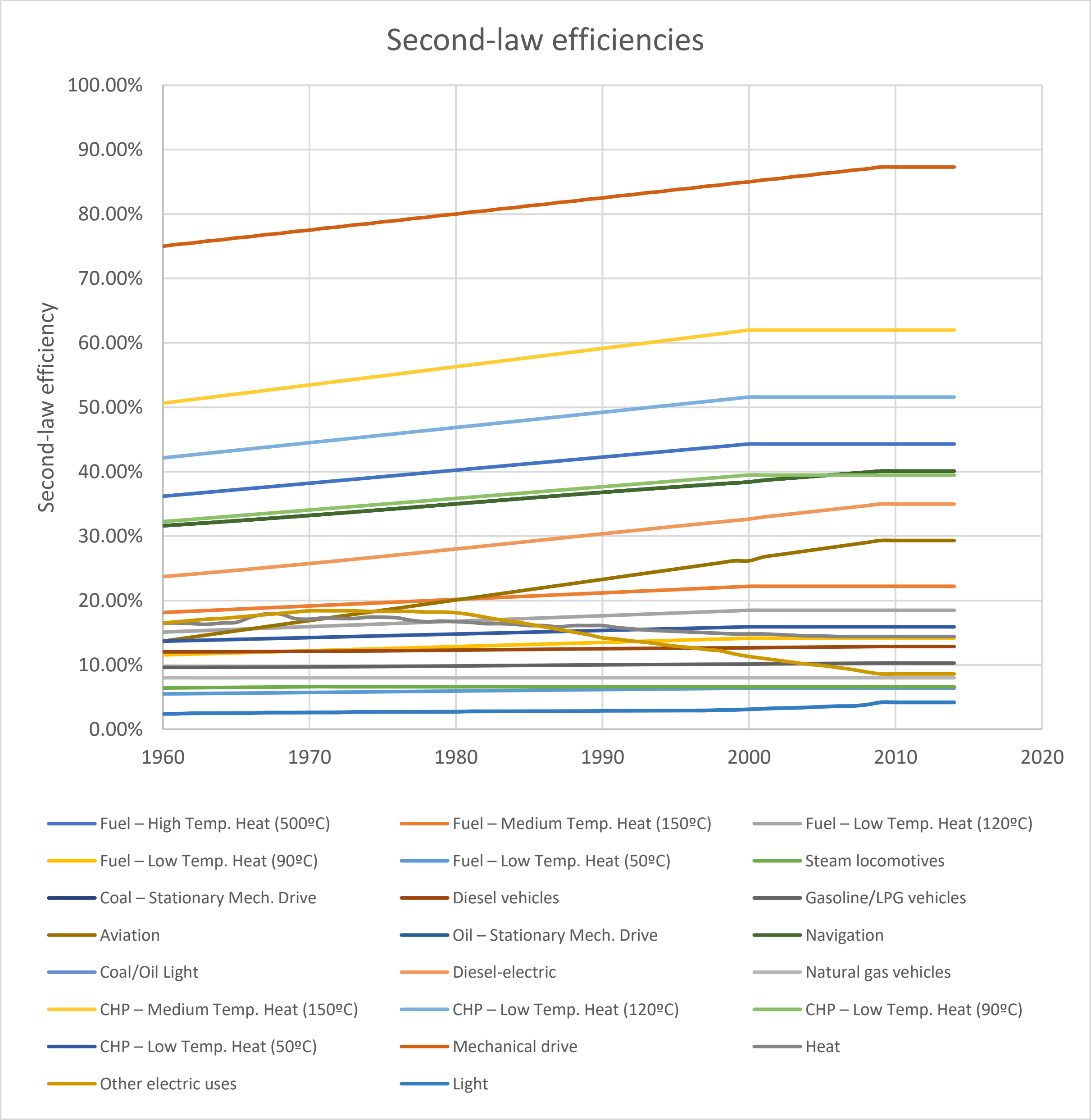

Figure 4: Second-law efficiencies of all end-uses.

2.1.4 Useful work

In the final step of the useful work estimation process, exergy efficiencies are applied to the final exergies found in 2.1.1 to compute the desired outcome – useful work. This is happening by multiplying the final exergy FEx_{ecp} of an energy carrier product *ecp,* which falls into a certain end use category *k* (Table 2), with the respective 2nd-law efficiency, for each year *y*, as in eq. (16). Then, all these useful work values of the individual energy carriers products, are summed up for every end-use category, as in eq. (17). Lastly, the new values of each end-use category are summed up for each useful work category *i* (see This allocation is based on the mapping for energy end-uses made by IEA, acquired from the supplementary data of Serrenho et. al [5]. These end-uses and respective useful work categories are listed in Table 2.

Table 2), as in eq. (18). This allocation is based on the mapping for energy end-uses made by IEA, acquired from the supplementary data of Serrenho et. al [5]. These end-uses and respective useful work categories are listed in Table 2.

$$U_{ecp,k,y} = FEx_{ecp,y} * \varepsilon_k \qquad (16)$$

$$U_{k,y} = \sum U_{ecp,k,y} \qquad (17)$$

$$U_i = \sum U_{k,y} \qquad (18)$$

The final results for the useful work of each category as well as the total useful work of Greece estimated are presented in Figure 5, while the respective shares of each category are displayed in Figure 6.

Overall, it can be observed that total useful work had a relatively linear increase from 1960 to 2007, driven primarily by the proportional increase of mechanical drive. Quantitatively, the total amount was 17300 TJ in 1960, growing more than 1000% until 2007, and reaching almost 204000 TJ. Simultaneously, mechanical drive held 40.6% share of the 1960's total reaching 69.7% in 2009. In 2007, matching also the decline of final exergy (Figure 1), the total useful work decreased in a stable linear drop until 2014, driven primarily by the mechanical drive uses' drop, which, with a two year delay, started in 2009.

Regarding the other useful work categories there is a variety of behaviors along the time series, with all having far lower shares of the total compared to mechanical drive. Muscle work held an important share of 25% in 1960, however, this category started decreasing logarithmically since, falling to under 5% in 1973 and reaching as low as 1% in the last decade of the studied period.

Observing heat categories separately, HTH started with a small share under 10% in 1960 and increased to be about 15% of the total useful work around the mid 1970s. Then, following a small drop to less than 5%, the category's share increased to around 18% in the mid 80s and kept decreasing ever since. Since HTH is related to heavy industry processes, this decrease could be explained with the slower industry development in Greece, as mentioned before.

Looking at MTH, the categories shares were oscillating above 20% up until early 1980s, decreasing afterwards and roughly stabilizing to just above 10% ever since. Finally, LTH category's share started as low as 5% in 1960 and raised to above 10% in early 1970s, oscillating at that level until the end of the series. This is logical since LTH uses are mainly for space heating and there is a standard amenity for the majority of buildings in the country. However, if the three heat categories are taken as an aggregated one – heat - (Annex Figure 7), it can be seen that associated useful work is close to the mechanical drive's until 1974, but then it drops as much as to half compared to mechanical drive for the rest of the years, until the financial crisis.

The useful works of light and other electric uses have always been low, holding a share of less than 1% and 4% respectively for the entire time series.

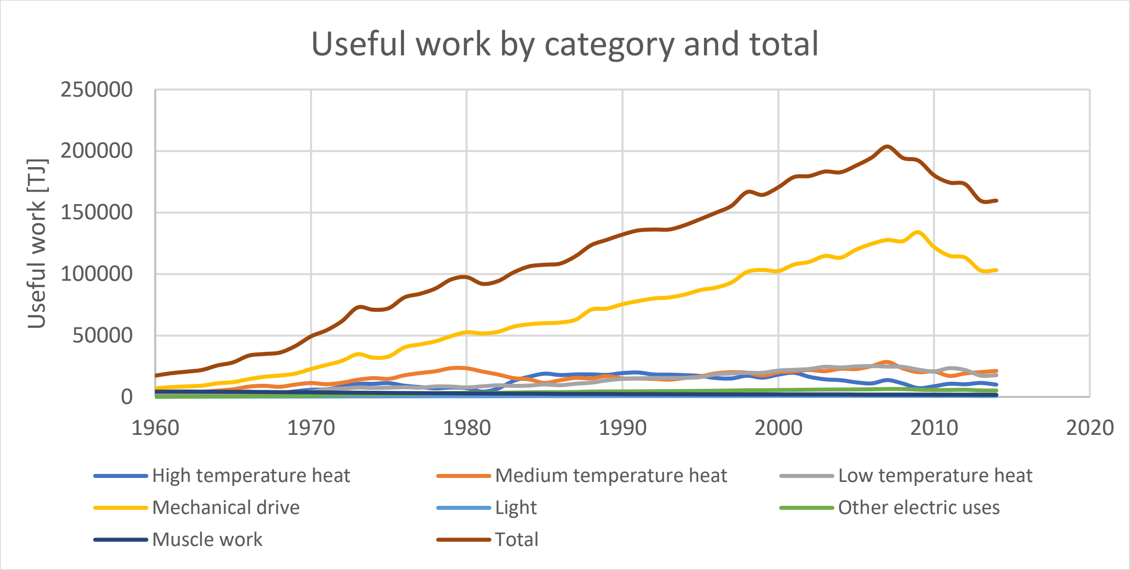

Figure 5: Useful work by category and total for Greece, 1960-2014.

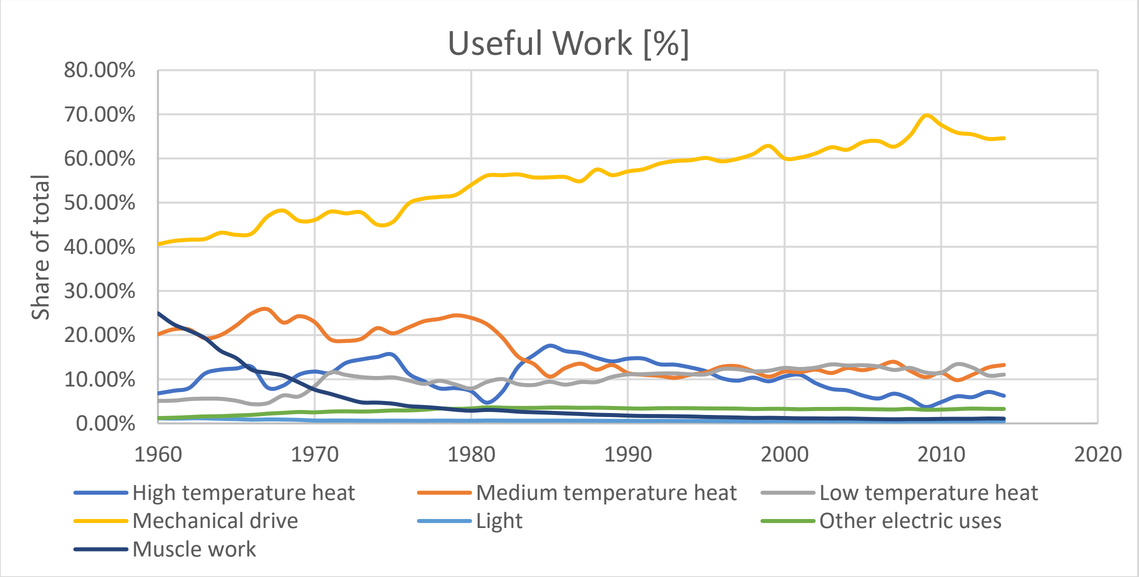

Figure 6: Useful work categories' share of total in Greece, 1960-2014.

From another point of view, Figure 7 is presenting the distribution of useful work in Greece for the different energy sectors. From the graph, it is clear that the highest amounts of useful work have been produced in the industry sector from the beginning of the studied period up until 2007, when there is a significant drop. Industry is the most consuming sector of useful work as it has associated end-uses with the highest exergy efficiencies: HTH, MTH, stationary mechanical drive and electricity mechanical drive. Transports and other have also high values of useful work associated throughout time. Other sectors even become the most useful work intensive sector after 2007 and remain relatively high ever since, because Greece always had strong residential activity and was focused in services, even after the crisis.

In transports, the useful work produced drops sharply after 2009 following the financial crisis, since transportation is a prime lever of economy, but is influenced as well.

The work generated for energy industry’s own use is not as high along the year as the other three sectors, but still quite considerable and follows a similar rising trend from 1960 to late 2000s, when this increase stops along with growth of the country.

Finally, the useful work of food and feed, which is essentially the muscle work, is not significant after the first couple of decades of the time series as explained earlier.

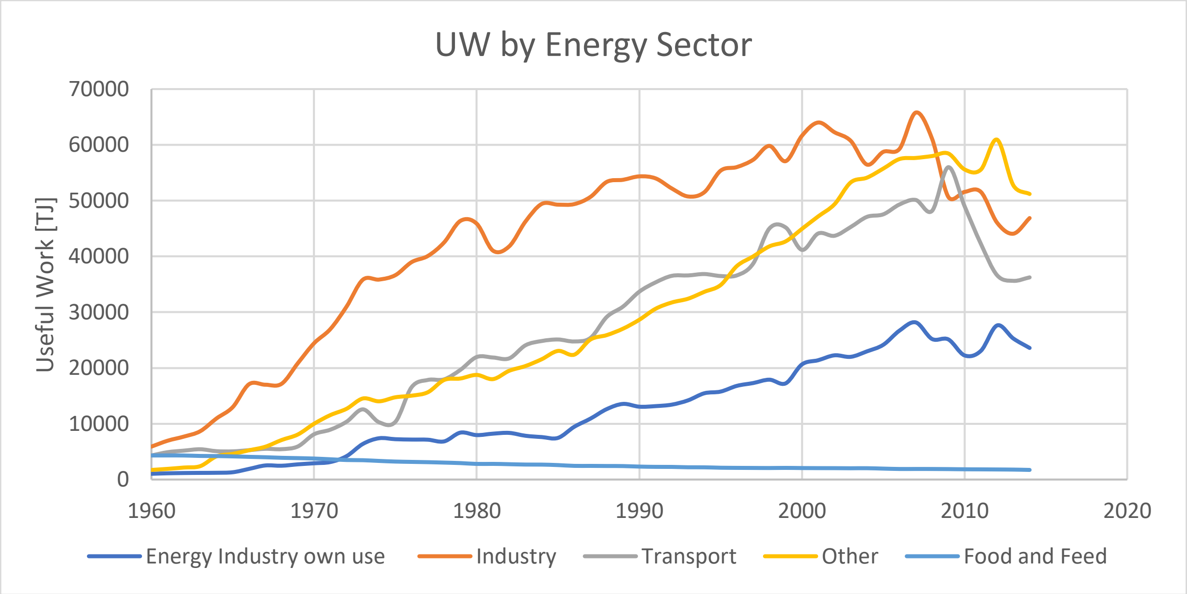

Figure 7: Useful work by energy sector in Greece, 1960-2014.

2.1.5 Aggregate Final-to-useful second-law efficiency

As a further step, knowing the final exergy and useful work amounts used in Greece from 1960 to 2014 it was possible to calculate the aggregate final-to-useful second-law efficiency of the country for this period. This is simply equal to the ratio of useful to final exergy for each year, as in eq. (19). The same was applied for each useful work category and energy sectors and the results are displayed in Annex Figure 12 and Annex Figure 13 respectively.

$$\varepsilon_{ag_y} = \frac{Useful\ work_y}{Final\ exergy_y} \qquad (19)$$

The results of the aggregate final-to-useful exergy efficiency for the entire series are displayed in Figure 8. It can be seen that the aggregate 2nd-law efficiency was quite low in 1960 compared to other EU-countries [5], having the value of 9.21%. Nevertheless, the efficiency seems to be increasing asymptotically throughout the time series until 2010. There is a fast growth in the first two decades of the time series reaching 17.3%, something that could be explained by the reverse decrease of muscle work in share (which has a very small efficiency).

Next, there is a further slower increase until around 18-19%, because of the relatively stable shares of MTH and LTH, which have lower 2nd-law efficiencies and the simultaneous share increase of mechanical drive, which has a higher aggregate efficiency.

Finally, there is a small jump to 20% in the four last years of the series. This is probably due to the significant drop of useful work consumption in the transport sector (Figure 7), which involves mainly technologies of diesel and gasoline vehicles with lower efficiencies, while the industrial and other sectors' useful work and aggregate 2nd-law efficiencies remained higher (Annex Figure 13).

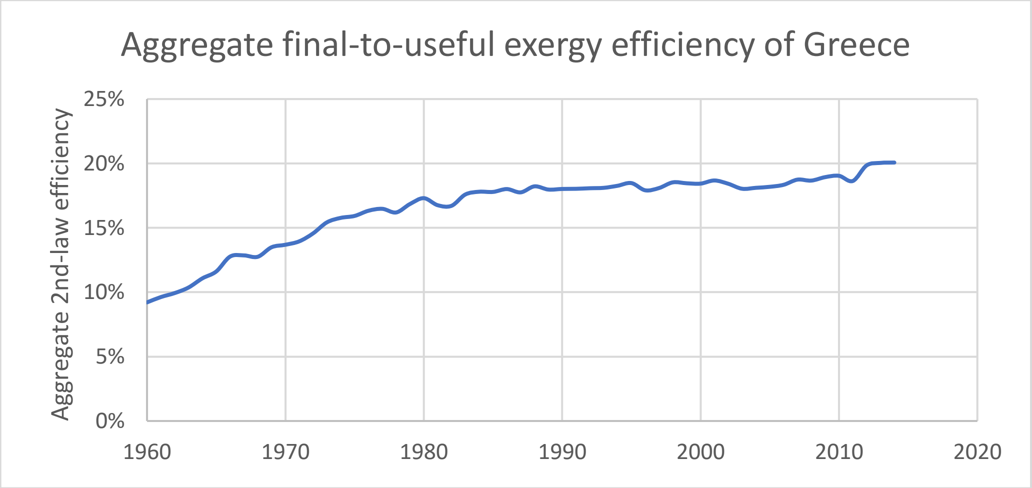

Figure 8: Aggregate final-to useful second-law efficiency in Greece, 1960-2014.

2.2 Economic Analysis

Before the 1950s, because the growth theory lacked an empirical base, it remained qualitative, and it was only after the development of the system of national accounts (SNA) that it became possible to construct historical figures of the gross domestic product (GDP), for a few prior decades. Up to that point, most economists believed that economic growth was driven by the accumulation of capital stock per worker. However, briefly later, with the use of perpetual inventory method (PIM), it was shown that this assumption was not correct. Instead, an aggregate production function of capital and labor services was introduced by Solow and Swan [1], [28], [29] This was a decisive novelty in growth theory and allowed economists to consider the relative significance of the two factors of production and sources of productivity growth [2].

These two primary factors of production which are capital (services provided by factories, machines, vehicles etc.) and labor (measured by the number of hours worked by people) are what enables economic value to be created. More specifically, the contribution of each factor to the GDP is proportional to what each receives from the GDP as well. In general, averagely across the world one third of the GDP generated income is devoted to capital (rents, interest, dividends) and two thirds to labor (wages), which means that annually the contribution of capital and labor to GDP are 1/3 and 2/3 respectively [4]. Eventually though, Solow [1] discovered that when considering as relative factors only capital and labor, they could not account for the entire observed growth in the US GDP. This difference between the estimation of the function and the measured GDP was identified by some as the ‘Solow residual’. Eventually, this residual was attributed to a factor defined as a qualitative ‘neutral’ time-dependent multiplier for the labor-capital combination. More recently, the yearly increment of this multiplier was linked with the increases in the total factor productivity (TFP) of a country [2].

In the neoclassic theory, TFP is assumed to be a not quantifiable exogenous factor, that has also been tried to be explained by technological progress. In order to explain this relation, first goods and services have to be considered as things, that when there is higher demand for them, their prices rise, profits increase, labor competition rises and also wages increase. This leads to even higher demand for goods and services. However, bigger wages encourage producers to become more efficient and then they increase labor productivity. This is supported also through investment in new capital equipment, assimilating ultimately more modern technology. Considering these interrelations, a new aggregate production function has been established since , including the TFP multiplier, it is called the Solow-Swan model and is widely used to estimate GDPs [2].

2.2.1 Trajectory of Greek economy up to date

Before moving further into the economic theory and presenting the past economic figures of Greece, it would be of benefit to first to explain the county's trajectory from the beginning of the examined time series. This can give a better understanding of the situation in which the Greek economy is today.

In the beginning, meaning the period between 1960-1973, like many countries of Europe, Greece went through what it seemingly appeared as a 'Golden Age'. In these years, the annual growth rate averaged around 8% outperforming major European economies. At the same time, inflation (Annex Figure 16) and unemployment rates (Annex Figure 18) were low, while the investment reached record high levels (Figure 23) and the budget balance was for a brief period in surplus (Annex Figure 14). The productivity of labor was rising with a rate faster than most European countries. Apparently, Greece was promising to do business because it had credible monetary policies, there were labor cost increases, the restrictions in trade decreased and the tax regime was favorable. As a consequence, the GDP per capita, which was just 60% of the average level of the present EU countries in 1960, rose close to 80% in the early 1970s [30].

These positive indexes however, show only part of the story of the rapid growth observed in the Greek economy. During this period, the elected governments up to 1967, and more intensively the following military dictatorship, were consecutively borrowing money. Specifically, in dictatorship years, between 1967 and 1974, the loans taken surpassed more than three times the sum of money borrowed by the Greek state since its founding in 1828. This is a factor that helped the rapid growth of GDP per capita, in comparison to other countries which needed decades to achieve. Still, as percent of GDP, dept at that period was less than 30% (Annex Figure 15). Another mean of government earnings was the increase in taxation of lower incomes, while at the same time, taxes for businesses were lightened. Regarding government spendings, there was a constant rise throughout the whole period, showing highest rates during the dictatorship. Part of that money went to investment, such as public buildings and road network infrastructure. Nevertheless, the bigger one was absorbed for the gigantic enlargement of the public sector and the increase of its servants, whose permanence was shortly after established, regardless of productivity criteria. Tourism was recognized as a driving force of the economy and the sector was financed excessively. However, in contrast to that, craftmanship and small businesses were left without financial resources, something that later led to the shortage of commodities. Yet, at the same time larger businesses increased. A result was the negative gap between exports and imports to exponentially increase. Public insurance and pension systems were never reformed so the expenses for the sector kept growing. Depts related to agriculture and businesses were spared to the debtors. Finally, a constantly increasing share of the spending was devoted for repaying national dept and its interest. Eventually, the lack of goods, followed by the oil crisis of 1973, and the fall of the dictatorship in 1974, led the inflation in that year to climb very rapidly from 6% to more than 30% [31]–[33]. After that point, the high performance of economy started to slow down. In 1974 the country returned to democracy.

In 1975 Greece applied to join the European Economic Community and that goal dominated economic policies. For the years to come the GDP kept growing up until 1979, however after that, a period of depression was entered. In the next eight years, the GDP was still at the same level (Figure 9), while the other European countries' continued to grow. Following, the GDP per capita fell once again to levels similar to before 1960. In 1981 Greece joined the European Union, an event that could be linked with the fall that was to happen almost three decades later. In the 1980s, a stagnation of economic activity was evident, inflation (Annex Figure 16) was higher and lasted longer than in other European countries and unemployment increased as labor productivity decreased. Simultaneously, the government finances started getting out of track, with fiscal policies that led to double digit fiscal deficit, devaluation of the currency, loss of competitiveness and a sharply rising public debt (Annex Figure 15) which almost tripled in the decade between 1980-1990. Despite that, inside an atmosphere of macroeconomic populism and an attempt to aid the 'less privileged', lower incomes rose and employment in public sector kept growing. Meanwhile, the private entrepreneurship role was downgraded and product and labor markets were extensively regulated. The tax system became more complex which enabled further tax evasion and that accompanied by high marginal tax rates led to low business attractiveness and thus low foreign investment inflows [30], [34].

In the early 1990s, economic policies were reversed and characterized by attempts of fiscal adjustments, stabilization of monetary and exchange rates and liberalization of the economy. The Maastricht Treaty was signed in 1992 and Greece had a new goal which was to join the 'euro' single currency group. The following years, inflation (Annex Figure 16) decreased, debt (Annex Figure 15) stabilized around 100% of GDP and productivity improved. However, these indexes were not as good as in the other European countries. Overall, until the end of the decade, there was a slow-rate convergence [30], [34].

Greece managed to enter the European Monetary Union in 2001. As proved later, this was done under false pretenses, since its government deficit and national debt were nowhere close to 3% and 60% that were the requirement limits respectively [35]. That year coincided with more economic growth and faster convergence to the rest of EU. As an example, major investments and infrastructure constructions were made for the Olympic Games in 2004 which boosted growth. Moreover, EU structural funds contributed in the economic performance, which this period had an average annual growth rate of 4% [36]. Having better credibility, the country was now able to borrow money with interest rates similarly low as e.g. Germany. Instead of trying to reduce the debt though, the country went through another wave of fiscal expansion. Additionally, growth was primarily driven by consumption while the government consumption was more than double of Eurozone (4.7% compared to 1.9%). Also, the growth rates of exports were similar as in other countries, but the growth of imports was greater. As a result, the country was functioning with fiscal and current account deficit up until the financial crisis [30]. As stated in the Lisbon Council, "Greece in the period 2000-2007 offers a dramatic example of unsustainable, boom-based growth acceleration pursued under weakening systemic growth forces" [37]. In 2007 the economy of the country peaked reaching the gross domestic product of 251 € billion (Figure 9).

After the international financial crisis of 2007-2008, the true problems of Greece's development nature came to the surface and simultaneously the start of the fall was marked. This new stronger recession weakened further tax revenues and caused the deficit to worsen. In 2010, the financial rating agencies graded Greek bonds very low, then capital started drying up and Greece faced a hard liquidity shortage.

The government was thus forced to seek bailout funding. The body that took on the task of providing and regulating the necessary support was Troika, formed by the European Commission (EC), European Central Bank (ECB) and the International Monetary Fund (IMF). Necessarily, the first bailout programme was approved and was aiming for adjustments to improve the competitiveness and the fiscal situation of Greece. Later a new programme which included pension reforms, privatisations and reform of labor and product markets was signed. Overall the direction was to cut spendings and increase tax revenues. Namely, these progammes also called memorandums, that imposed austerity measures, were agreed in order to avoid the country being forced to exit from the Eurozone, with any consequences this could mean for all parties involved [30], [35].

Nevertheless, these reforming adjustments, including the austerity measures, led inevitably to the creation of a vicious cycle of recession. Unemployment reached as high as 26% in 2012, tax revenues were weakened, and Greece’s fiscal position rendered worse. Consequently, this situation created a humanitarian crisis and led to poor progress of institution quality. Overall, the Greek economy shrank by 26% between 2007 and 2014 and the dept climbed up to 180% of GDP in 2018. Some might say that instead of working as a remedy for the domestic economy, the bailout programmes have primarily served to ensure that the creditors are getting paid back, while seemingly, indexes, like budget surplus and growth rates, are becoming positive. Meantime, the government is putting together what little is left to give the citizens [35], [38].

The purpose of this section is not to point fingers at any specific direction or put blame on any particular party. Decisions in the past where probably taken as they were considered beneficial for that time point, and maybe some decisions could have been made differently. The intention is to show that one of the main reasons that led to the current state, is the mentality to not realistically assess the economic state and possibilities of the country, and plan and act respectively, but rather take decisions that bring interim results, while passing any created issue on. This mentality seems to be hereditary and is usually linked with short-term political benefits. The results, after decades of such practices, have led the country to its tipping point. Now, the challenge for Greece is to change certain habits that have been proven undermining, overcome the vicious loop of recession, and start to grow sustainably inside a new framework.

2.2.2 Financial Figures

In this subchapter related theory and financial figures of Greece for the period 1960-2014 are displayed and explained with the scope of using possible finding in the process.

2.2.2.1 Gross domestic product

The gross domestic product (GDP), symbolized as well by Y, is expressed in monetary units and is the standard measure for the size of a country’s economy. The production function used to estimate it is of Cobb-Douglas type adapted on the Solow and Swan theory and is given in eq. (20) [2]. The A_t stands for the TFP, K_t for the capital, L_t for the labor of year t, while α_L and α_K are the shares by which labor and capital contribute to GDP respectively. These shares are complementary, i.e. $\alpha_K = 1 - \alpha_L$, and are kept constant throughout the years when used in the equation. In this case, the GDP is not calculated by the equation but directly given by PWT [11] and is shown in Figure 9.

$$Y_t = A_t * L_t^{\alpha_L} * K_t^{\alpha_K} \tag{20}$$

In the figure, roughly five different trends can be identified that can be explained with the brief historic trajectory described in the previous subchapter. First was the period from 1960-1974, which had an average annual growth rate around 8%, coinciding with the beginning of more intense industrialization and investment. Then was the shorter period after regime change, between 1974-1980, with still positive but lower growth. Following came the stagnant decade between 1980 and 1990, with very small positive or negative growth along the years, and enlargement of fiscal issues. Fourth was the period 1990-2008, with the progressively increasing growth, that led Greece to its peak financial development. This coincided with the planning prior and finally the entry in the single currency group. Finally, there were the years of the Greek crisis, from 2008 and till the end of the time series, characterized by aggressive recession.

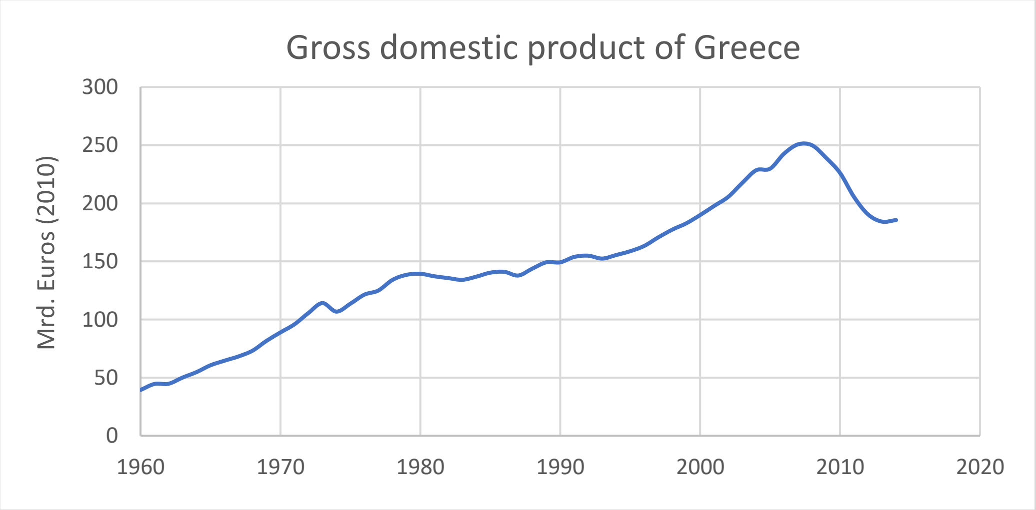

Figure 9: Gross domestic product of Greece in billion euros of 2010, 1960-2014.

2.2.2.2 Labor

Moving forward, Figure 10 displays the labor and capital shares of the income distribution in Greece, provided by the two different databases of Penn World Table [11] and Annual Macro-Economic database of the European Commission (AMECO) [39]. The data of AMECO show a wide difference between the labor and capital for more than half of the time series. For this reason, the PWT data are chosen instead and are used further. The average shares for PWT are 52.61% and 47.39% for labor and capital respectively, quite far from the 2/3 and 1/3 that represent roughly these averages across the world [4].

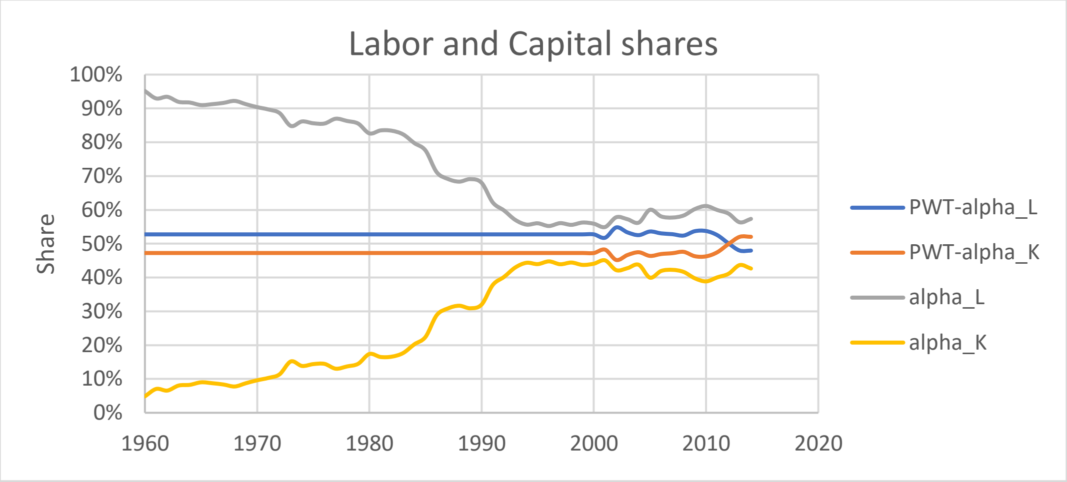

Figure 10: Labor and capital shares of Greece by PWT and AMECO, 1960-2014.

From the PWT [11] were also acquired the average annual working hours per capita of Greece, which are displayed in Figure 11. It can be seen that, the average annual working hours begin higher than 2200 h/a in 1960, decrease almost linearly for the next decade and then stabilize around 2100 h/a for the next 30 years. The significant drop in the first decade could be related to the fast growth of GDP, while the almost constant trend between 1970 and 2000 might be attributed to lack of yearly data. After 2000, the working hours have been oscillating which reveals the existence of yearly data and could translate into strong changes in the labor scene.

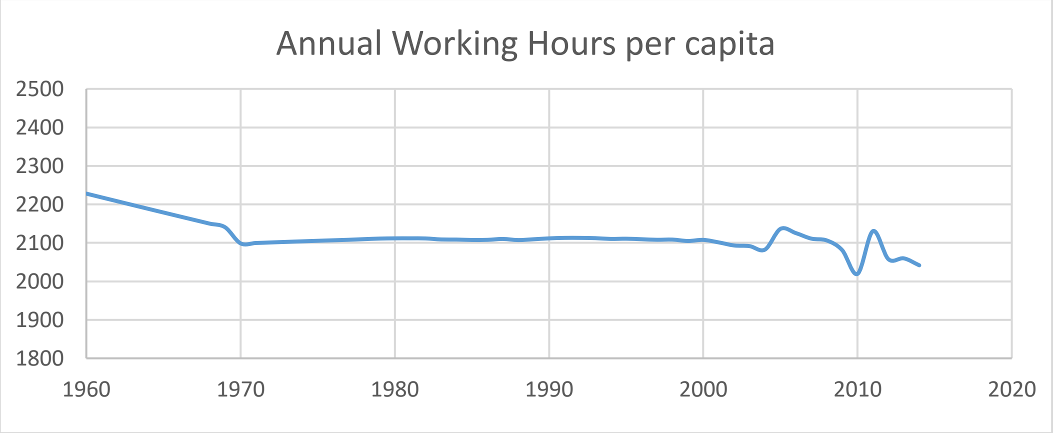

Figure 11: Average annual working hours per capita in Greece, 1960-2014.

The employed population data of the country for 1960-2014, was taken from AMECO [39], and the numbers are shown in Figure 12. The numbers started from less than 4 million in 1960 and surpassed that ceiling in late 1990s. Following the growing population and economic growth, the employed people reached as high as 4.6 million in 2009. However, in the after-crisis years the numbers fell even lower than 4 million once again, because of high unemployment.

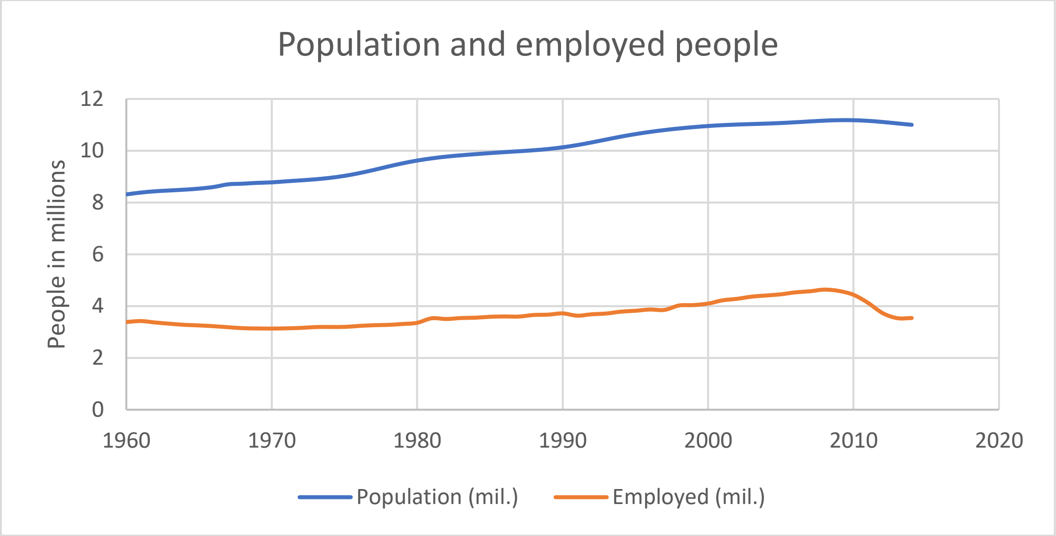

Figure 12: Population and employed people in Greece, 1960-2014.

The multiplication of the average annual working hours per capita and the employed population for each year gave the total working hours per year of the labor force, or just Labor (L), which is displayed in Figure 13. The total working hours start at 7.5 billion h/a and fall to 6.6 billion h/a in 1970, because of the decrease in working hours per capita and the employed people in the first two decades of the series, despite of the growing population. Ever since, Labor kept increasing until 2008, with 9.77 billion h/a. However, after the crisis the numbers fell greatly by 26%.

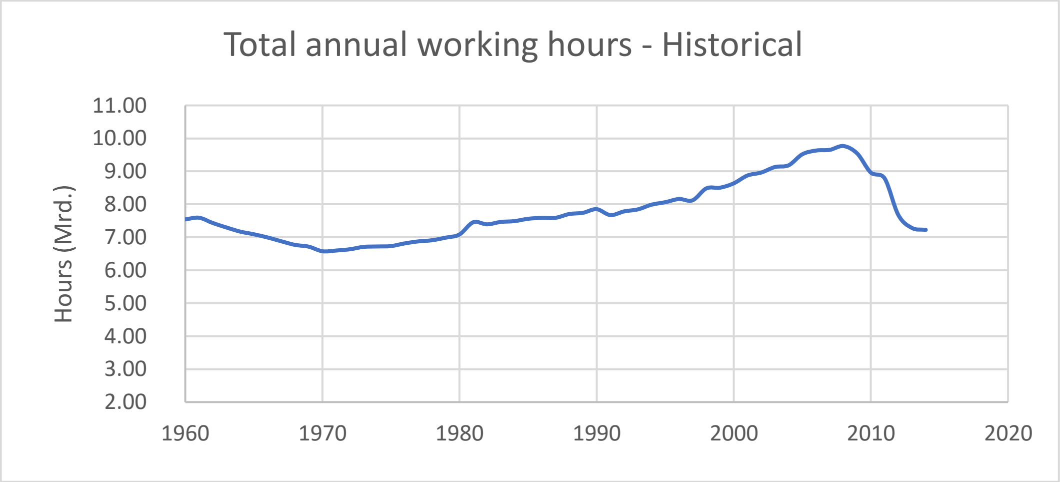

Figure 13: Total annual working hours of Labor force in Greece, 1960-2014.

2.2.2.3 Capital

The capital stock (K) of Greece, provided by [39], is presented in Figure 14. It started from as low as 118.14 € billion in 1960, peaked at 857.19 € billion in 2010 and mildly decreases since. Generally, it follows a rising trend similar to the GDP and its behaviour can be explained with the investment in capital (Figure 23) in the relevant years. From 1960 to 1980 the curve in relatively concave because of very high investment. Then, until 1993, it become convex because of small investment. Later it became concave again because of higher investment, until the crisis, where a significant drop is observed.

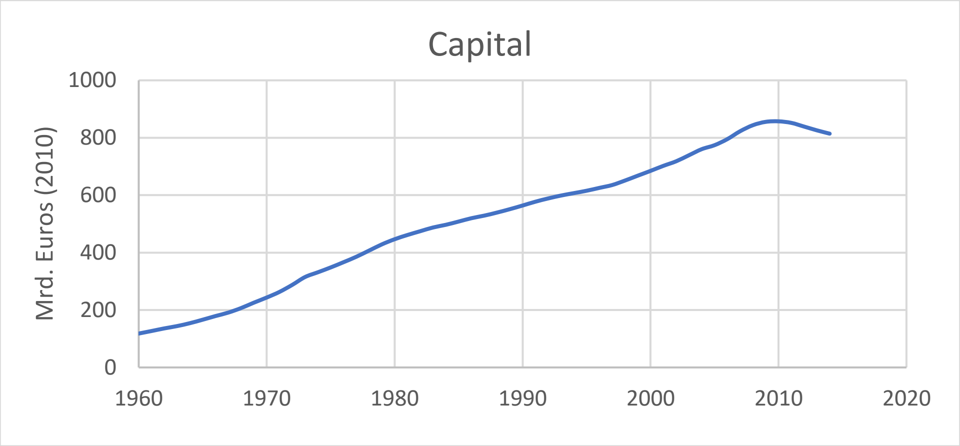

Figure 14: Capital stock of Greece, 1960-2014.

2.2.2.1 Total factor productivity

When using a production function which considers only labor and capital, meaning eq.(20) without the TFP term, as expected, the output is not close to the historical GDP of Greece. This is clear in Annex Figure 17. In order to estimate the Solow residual, as in the Total Factor Productivity, eq. (20) was solved this time for *A* (or TFP). The results are depicted in Figure 15 and will be addressed as real TFPs. Moreover, the TFPs are indexed by dividing the value of each year with the one of the first year. The outcome can be seen in Figure 20.

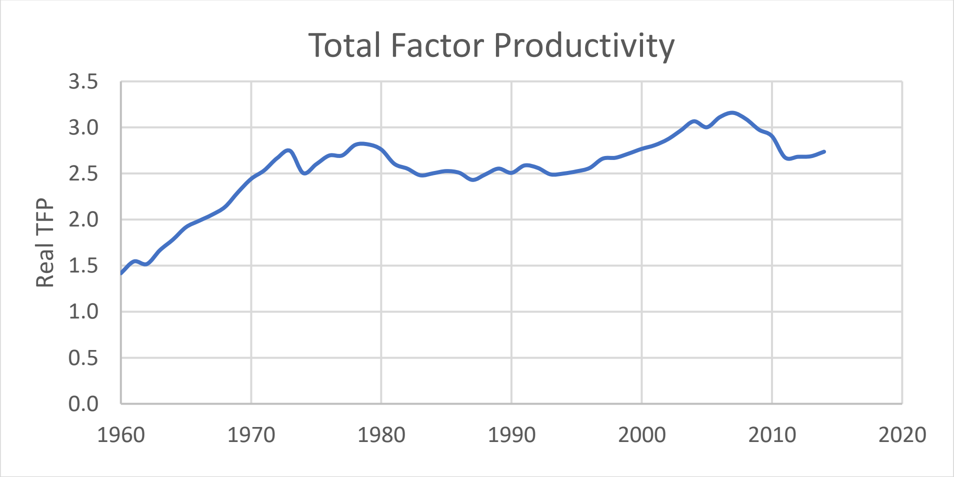

Figure 15: Total factor productivity for Greece, 1960-2014.

2.2.3 Correlation of Exergy with Economy

At this point the correlation between final exergy and useful work with GDP is going to be examined. The final exergy intensities and useful work intensities are created by dividing final exergy and useful work with GDP - using *euros of 2010* as reference - for every year, respectively. The created trends are displayed in Figure 16.

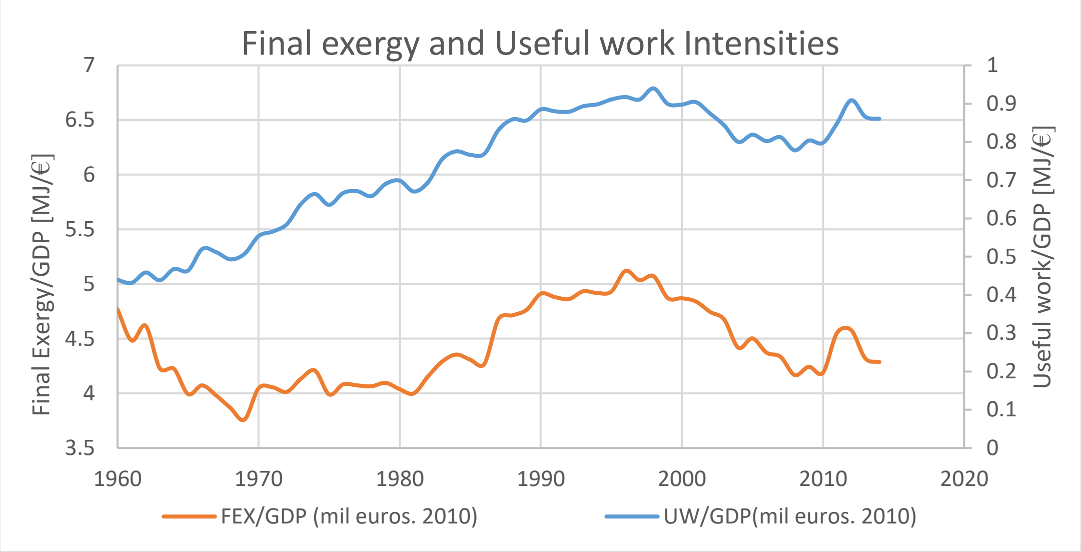

Figure 16: Final exergy and useful work intensities for euros of 2010 in Greece, 1960-2014.

The *final exergy intensity* of the country oscillates around 4-5 MJ/€ in the examined time series, showing a concave part from 1960 to 1985 and a convex part from that year to 2010. It starts at 4.8 MJ/€ in 1960 and quickly drops under 4 in the first decade, showing a reduction in need of exergy sources for creation of economic value. This could be explained with the rapid decrease of feed exergy needs, while the industry started growing and contributing in economic growth.

After a small increase, during the next decade the index oscillates slightly over 4 MJ/€ until 1980. A result coming from the simultaneous big increase of exergy usage in industry, transport and other sectors, while the feed kept falling with lower pace.

Further increase of final exergy in transportation and other sectors, but not in industry and GDP led to increase of the index up to around 4.8 MJ/€, in 1990. This period could be explained with the increase of energy carrier use in relevant non-productive activities, e.g. fuel use in individual cars and domestic acquisition of electric house appliances, or maybe the growth of an inefficient public sector.

Later, in the decade 1990 to 2000, the index oscillates close to 4.9, explained by a further increase of exergy in industry and a faster growth in GDP.

The period until 2007 showed an even faster growth of the GDP, with less need for exergy increase in industry and the rest of important sectors, resulting in quick drop of the intensity. The transition of economic activity from processing to the service sector and the renewal of cars, equipment, etc., as a result of economic development, are some of the factors that led to this improvement.

After the financial crisis in 2007, the index kept reducing reaching about 4.2 values in 2010, reflecting the quick drop in industry, and from another point of view, the decrease in oil and coal related fuels. The spike in the last four years is explained with the faster drop in the economy compared to the exergy injected in it.

When looking at the curve of *useful exergy intensity*, similarities and differences to the final exergy intensity can be observed. The first part of the curve from 1960 to 1985 keeps a constant increase, while the second from 1985 to 2005 is convex. This happens because the aggregate final-to-useful second-law efficiency is rising fast from 1960 to 1980 and slightly more until 1985, but then stagnates for about 15 years.

The rapid decrease of muscle work from 1960 to 1980 and the booming useful work produced in industry the same period, implies, the shift from agriculture and physical work to mechanical drive. Alternatively, the industrialization as driver of economic growth is shown. Nevertheless, as suggested in [5], [8], [40], countries going through an era of industry development show increase in the useful work intensity index.

Next, in the decade 1980-1990 there is a further rise of the index, because of the small economic progress and the constant increase of UW in transportation and other sectors (while closing their gap with industry). At this period, the aggregate 2nd-law efficiency was relatively stable.

Then, the fast growth from 1990 to 2007, with not such a significant useful work production in industry, transport and other sectors, resulted in a drop of the useful work intensity.

Finally, and similarly to the final exergy intensity, the ratio increased anew, because the GDP drop in the last year of the time series was more intense than of the total useful work in society.

Overall, the index seems to become relatively stable after mid 1980s and until the end of the time series, oscillating between 0.77 and 0.93. Specifically, the average is 0.86 MJ/€. It could be said that, in the case of Greece, for euros referenced to 2010, and for this period, the relation between UW and GDP is relevant to this index value. Still, additional analysis on the matter could be done the next decades, to investigate further if this correlation is steady or not.

In the case of estimating the final exergy and useful work intensity for GDP in *euros of 2000*, the results are shown in Figure 17. Regarding useful work, the intensity is displaying values between 0.6 and 1.4 MJ/€ (or MJ/€) throughout the time series, while the average of the trendline is 1.09, which is close to one. This finding comes to support the theory of MEET2030 [4], that usually there is a strong correlation between the Useful work produced in a country and the economic output of it, which in that case was translated as UW/GDP≈1, i.e. in order to produce one € of GDP, one MJ of useful work is required. Still, this correlation seems to be different between countries, as shown in Figure 18 by Serrenho et al. in [5]. Based on these findings, it is important noting that, the scale of the index depends on the currency it is referring to.

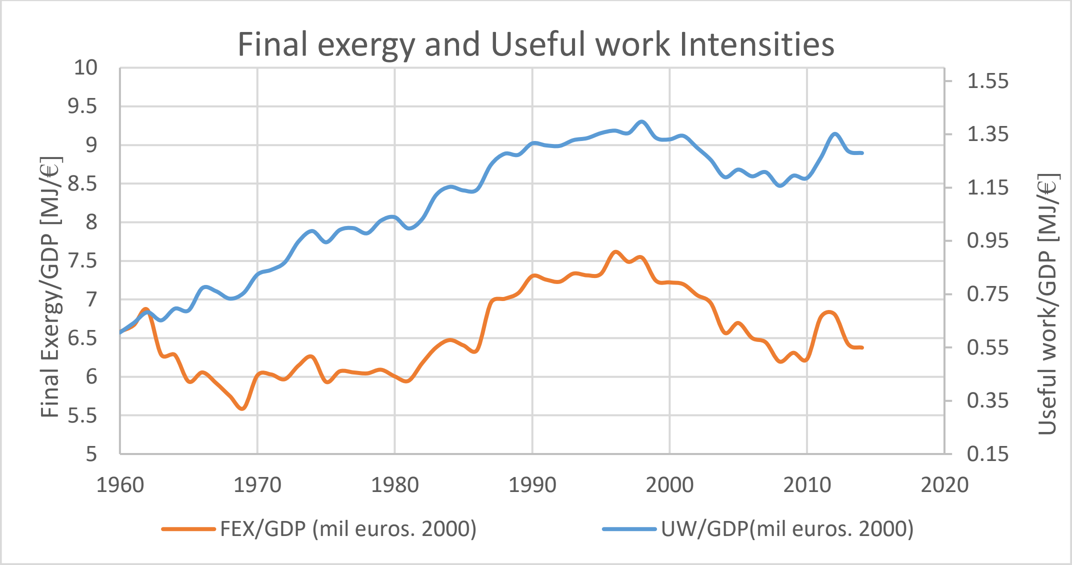

Figure 17: Final exergy and Useful work intensities for euros of 2000 in Greece, 1960-2014.

Moreover, the findings of Serrehno [5] presented in Figure 18 are showing that, economies while getting industrialized have useful work indexes that tend to increase. This is something observed mostly in southern European countries (e.g. Spain, Portugal) that in the beginning of the examined series did not have a strong industry in comparison with their northern neighbours. It is also shown that, when an economy has passed the era of getting industrialized and the industry sector is developed, then the index starts stabilizing and eventually after some point decreases. This is seen mostly in northern European countries (e.g. Sweden, Belgium). This decrease might be linked with bettering the aggregate exergy efficiency of the countries, as well as with the services' sector becoming part of the mechanism to generate economic value.

Another point that can be made from the same image is that northern countries seem to show higher useful work intensities overall, since they need to produce more useful work related to space and water heating, because of the yearly lower atmospheric temperatures.

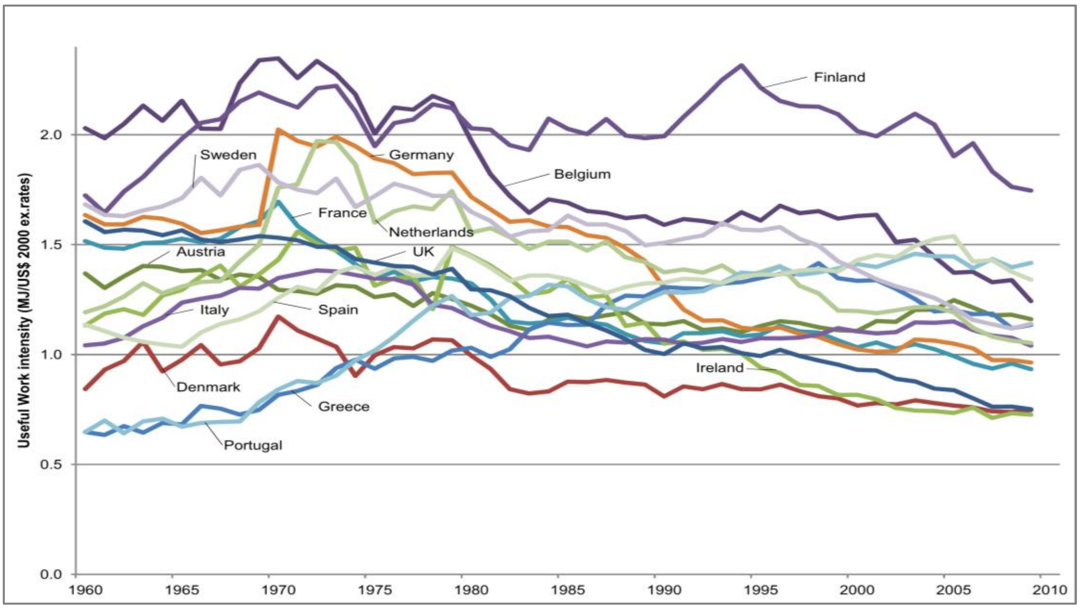

Figure 18: Useful work intensities for each EU-15 country from 1960 to 2009 [5].

2.2.4 Link between TFP and exergy efficiency

Every economic activity requires energy in order to happen, so, the economic development over the last century, mainly through industrialization, has been characterized by the rising employment of energy consuming technologies. This necessarily led to an extended demand for energy. Namely, Ayres and Warr [41], for the case of the US between 1946 and 2000, showed that to maintain long-term growth, either increase in energy supplies or increase in efficiency of energy usage is essential. In more detail, short- and long-term influence of exergy, as well as long-term influence of useful work in the creation of GDP were found. This could mean that, at any given point in time, more exergy use can lead to increase in creation of products and thus wealth generation. While on the long term, economic growth can be sustained by bettering the ratio of useful work per exergy injected, which translates to higher second law efficiency.

The MEET2030 study, which was addressing the past of Portugal [4], managed to empirically show a correlation between the aggregate exergy efficiency of the country and its total factor productivity. To do that, the ratios for each year, of the logarithm of the indexed TFP and of the logarithm of the efficiency ratio, were calculated. By efficiency ratio is meant, the aggregate efficiency of every year divided with the efficiency of the initial year of the time series. This relation is shown in eq. (21). The resulting ratio was roughly constant (*c*), meaning that the exergy efficiency approximately linked to TFP and economic growth.

$$\frac{\ln\left(\frac{TFP_t}{TFP_0}\right)}{\ln\left(\frac{EFF_t}{EFF_0}\right)} \approx c \qquad (21)$$

The same process was followed in this work for the case of Greece and the results are presented in Figure 19. It seems that the ratio between the two logarithms in the last 40 years is close to one, while the average is 1.05.

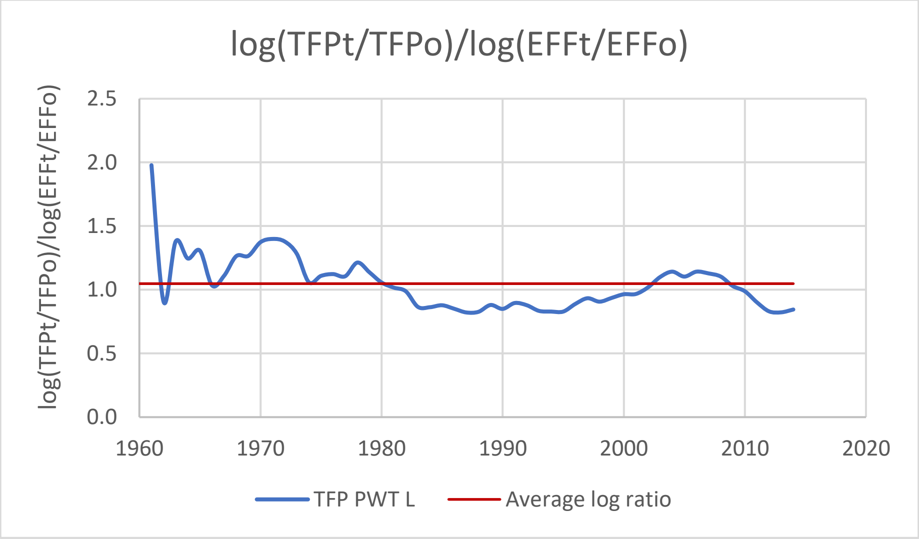

Figure 19: Ratio of logarithms of TFPs and 2nd-law efficiency ratios for Greece, 1960-2014.

In the process following MEET 2030, there is the attempt to estimate a new indexed TFP based of the aggregate second-law efficiency of the country. This is done using eq. (22), which necessarily is the inverse process for the ratios of logarithms used above. However, instead for a different exponent every year, the average of the ratios of logarithms (1.05) is used, with the logic of trying to establish a constant relation. In that manner, the new estimated indexed TFPs are displayed also in Figure 20, along with the indexed from the real TFPs. As expected, the two curves are close, with the difference that the estimated TFPs do not fluctuate similarly to the indexed TFPs, but rather follow a similar trend as the one of the aggregate second-law efficiency evolution. This makes sense since the exponent is constant.

$$TFP = \left(\frac{EFF_t}{EFF_0}\right)^{1.05} \qquad (22)$$

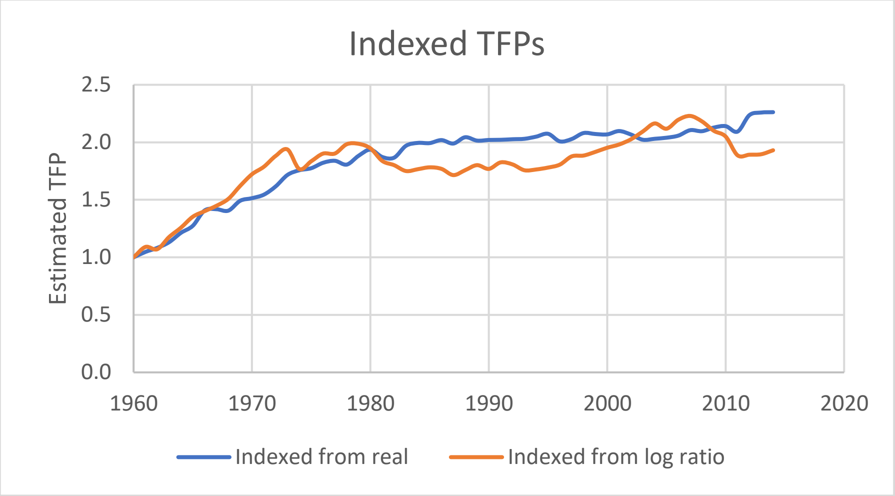

Figure 20: Estimated indexed TFPs from ratio of logarithms and from real TFP in Greece, 1960-2014.

Chapter 3

Scenarios

The purpose of this chapter is to develop scenarios for the future development of factors which influence the economic growth of Greece. To do that first two labor scenarios, then two capital investment scenarios and finally, and most importantly, two aggregate exergy efficiency scenarios will be created. The more pessimistic cases of labor, capital and efficiency are meant to be combined in a main scenario, while the same will happen for the more optimistic cases of the same factors, which will be coupled in another main scenario.

3.1 Labor scenarios

In this subchapter, the two labor scenarios will be formed. Because labor depends on both the population of a country and on the employment among the people, one main population development projection will be assumed, and then considering two different economic growth possibilities, also two different unemployment rate paths will be speculated.

3.1.1 Population scenario

The forecast presented here for the evolution of the Greek population is one out of eight different scenarios, part of a study made by the Laboratory of Demographic and Social Analyses (LDSA), of the University of Thessaly, Greece [42] in 2016. It was published by the research and policy institute diaNEOsis [43]. The study addresses the period of 2015 to 2050. The methodology implemented is the cohort component method and takes under consideration demographic components of fertility, mortality and immigration. More relevant estimations have been made for the case of Greece from Hellenic Statistical Authority (2007), the Vienna Demographic Institute (2010), UN Population Department (2015) and Eurostat (2013), which gave valuable results. Nevertheless, the study presented here gives more thorough analysis of the estimates, takes under consideration more recent data, political and economic developments, immigration trends and uses a different methodology.

The scenario is driven by a concept of resilience for the Greek society. The course is based in the hypothesis of gradual return to 'normality' with mild growth rates and remaining in the eurozone. Moreover, not much further job-market deregulation, decrease in social expenses, as well as no radical changes in the public health system are assumed. Additionally, no further important decrease in the purchase power of households and progressive decrease in unemployment, especially of youths, is expected. This scenario also requires the gradual slackening of the associates' demands, accompanied with the logic of ɑ relative convergence to the framework of E.U. This could lead to low but positive GDP growth rates and the conservation of a minimal welfare state. That way Greece would not stray far from the development logic of the other western EU member states. This course concerns and influences the first two of the demographic components, giving: a) progressive increase in the life expectancy (with decelerating rates compared to the past) to about 82.7 in 2030 and b) increase of the fertility rates to 1.55 on 2030 from 1.34 that was in 2015.

Regarding immigration, mild inflows are expected in this scenario by the return of a few Greeks, but mainly from foreigners, most of who are coming from less developed countries. On the other hand, outflows would be of more Greeks than those returning and of fewer foreigners than those entering the country, leading overall to a positive immigration balance.

Ultimately, all the above factors are anticipated to lead to a relatively constant decreasing trend of the total population, as displayed in Figure 21.

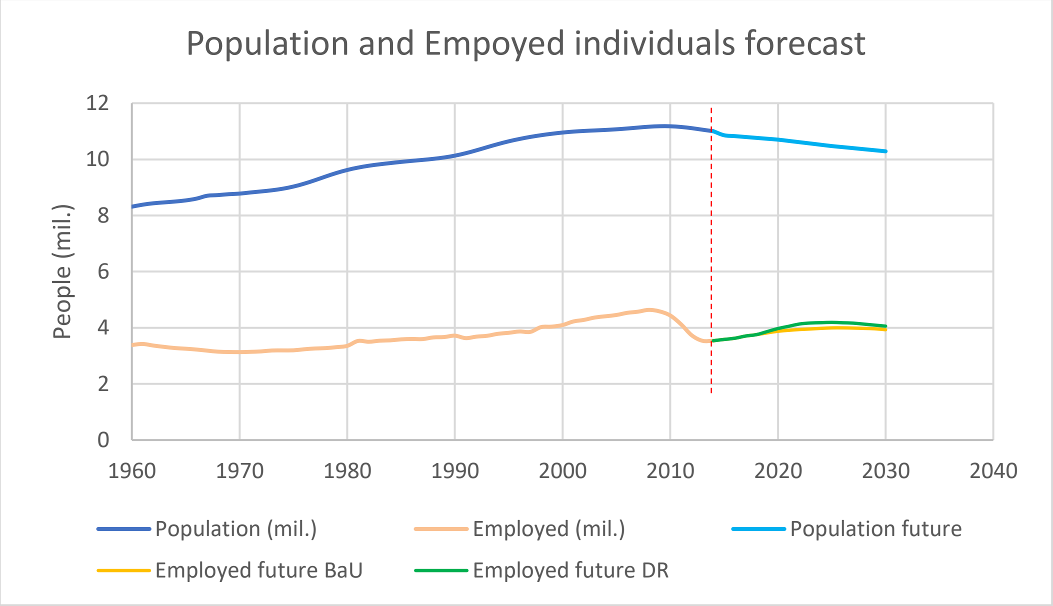

Figure 21: Forecasts for the population and actively engaged individuals up to 2030 in Greece.

Nevertheless, despite this relatively optimistic scenario, very crucial factor is the population distribution in different age groups, which had been created until the beginning of the prognosis. The small fertility rates of the past and the increasing life expectancy of the population have led to the overall aging of the nation throughout the past decades. In detail, the base of the population pyramid of Greece is shrinking as time goes by, intensifying this way the 'aging of the pyramid base' problem, which is a result of low fertility. Simultaneously, as the individuals of middle age groups move to higher ages, the problem of the 'pyramid tip aging' is also intensifying. It is thus inevitable for the numbers of the young population to decrease, while the opposite is expected for the elderly.

3.1.2 Unemployment and labor scenarios

Inside the frame of the assumed population development, the estimated section of productive age, i.e. 15-64 years old, is going to decrease from 7 million, or 64.5% of the total in 2015, to around 6.6 million people, or 62.7% in 2030. Consequently, this is going to lead to an inevitable decline of the actively engaged population in economic activities, as presented in Annex Figure 18. From another point of view, regarding unemployment rate, two scenarios will be assumed in order for each to accompany a different economic development.

In the first case, which will generally assume a mild progress of the country, the unemployment will follow the trend of the previous years (having dropped below 20% already in 2018 [39]) and will keep decreasing until it reaches the pre-crisis levels, where it stabilizes at 8%. The assumption has it that it will take more than 10 years to reach that level. Thus, from around 3.6 million working individuals in 2015, about 4 will be reached in the middle of the next decade. Then, following the decreasing total economically active population, it will decline smoothly until 2030 (Figure 21).

In the second case, which will coincide with faster growth and progress, the unemployment rate will also drop more rapidly and will eventually reach around 5% in an asymptotic manner. This would lead to almost 4.2 million working individuals by 2025, but then will start falling according to population as well.

Additionally, regarding the average annual working hours per capita, they are considered to stay constant after 2014 at 2042 h/a.

Note here that, the above presented numbers of the study were given in intervals of five years, from 2015, to 2030, so the in-between years were generated with linear interpolation.

Projections for Labor are made using the same method as in subchapter 2.2.2.2 and are based on the previous assumptions. The results, which are expressed in total number of working hours, in Greece until 2030, are displayed in Figure 22. For both cases it is shown that, after 2014, because of the drop in unemployment, there is an increasing trend until the middle of the next decade. However, later it curves down because of the further decrease of the population and the relatively stable unemployment rate. The second more optimistic scenario is displaying overall higher total working hours as expected. Still, the decreasing population and the simultaneous aging of the population are necessarily leading the number of people that will be working to be smaller. This would lead to total annual working hour levels of the mid-1990s for the pessimistic scenario, and early 2000s for the optimistic one, i.e. about 15% less than in 2007, when the economy reached its peak.

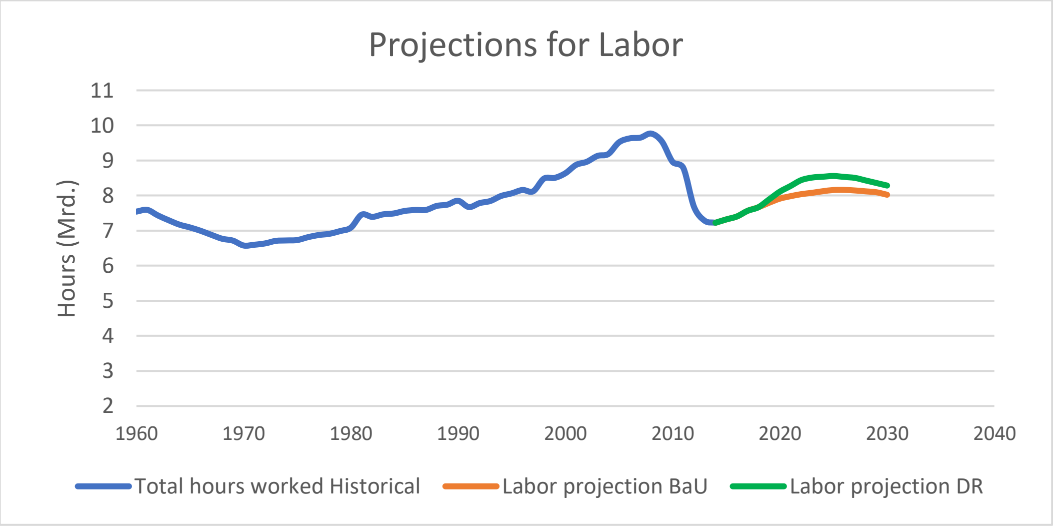

Figure 22: Labor in total annual working hours in Greece with projections to 2030.

3.2 Capital scenarios

In the national effort towards the revival of economy and the increase of employment, the quantity and quality of private profitable investment plays a crucial role. Before crisis, the investment capacity had reached levels of almost 26% of the GDP, in comparison to 13% in 2017-2018 [39], [44]. Yet, the majority was directed to internationally non-marketable sectors of economy, supporting this way a developing model of importation, deindustrialization and consumption. Gross investment in 2007 peaked at 62 € billion and after crisis fell as low as 22 € billion in 2017 [39]. More specifically, investment related to business in 2017 was 15.5 € billion, which is 8.5 € billion less than in 2007. Still, this amount is almost equal to the money needed for compensating the deteriorating capital of the existing businesses (15.1 € billion). As a result, the remaining amount is leading to a very slight increase of their capital stock, which is directly linked with increase in productivity and consequently for improving the living standards of the population.

Thus, it is essential to find a new balance point inside the Greek economy regarding the size and mix of private investment. The proper reforming policies should be promoted, in order to take advantage of the ending of the memorandums, as well as the international mobility of investment funds, and push towards the productive reorganization of the country. In EU the average investment capacity is 20% of the GDP, a goal that needs to be reached by Greece as well [44]. The challenge is whether this goal is going to be met or not, and if yes, how agile the country is going to be, in order to arrive to the target.

For the purpose of this thesis, two scenarios concerning the future investment in Greece will be assumed. The first one will consider a course within the already existing relative framework, while he second one will consider changes that are regarded necessary for a swift economic growth.

3.2.1 Business as usual scenario in Capital

Currently, Greece‘s framework still contains a lot of obstacles for conducting business and ranks very low among other European countries, when it comes to processes such as contract enforcement and justice, immovable property transfer, enterprise and university cooperation, access to loans and high taxation. Furthermore, civilians tend to spend a lot of their money in private consumption instead of saving for future investments [44].

Assuming that not important reforms take place and the current situation continues, then an annual pessimistic growth rate of 5% of investment is suggested for this scenario. The result of this assumption on the gross fixed capital formation (GFCF), as percentage of the previous year’s GDP, is shown in Figure 23, while in monetary terms, it can be seen in Annex Figure 19. Following this path, the GFCF is barely not going to achieve the 20% of GDP in investment goal by 2030. In monetary terms, only the 2002 levels are going be reached by the same time. This outcome is not very satisfying and does not look very promising for the rest of the economy.

Moving on, in order to estimate the future capital stock of the country as well, a projection for the depreciation rate of capital is needed. The consumption of fixed capital in the past (found in [39]) is displayed in Annex Figure 20 as percentage of the total capital stock. For the future projections, its average which is 3.4% is used.

The capital stock is estimated using eq. (23) of the PIM method, where K_t is the capital stock of year t, GDP_t is the gross domestic product, i_t is the GFCF as percentage of the previous year's GDP and δ_t is the depreciation rate, or else, consumption of fixed capital (CFC). In essence, in the right part of the equation, the $+i_{t-1}GDP_{t-2}$ is the investment of GDP in capital and $-\delta_{t-1}K_{t-1}$ is the capital that will not be available anymore because of depreciation [4]. Note that since the formula is taking under consideration also the GDP of previous years, the calculations are done in a loop after having estimated GDP as well in subchapter 4.1. Capital stock projections are shown in Figure 24. It is clear that, this scenario would lead to a rather stagnant development of the country's capital stock, which in that manner does not seem reaching the peak of 2010 soon.

$$K_t = K_{t-1} + i_{t-1}GDP_{t-2} - \delta_{t-1}K_{t-1} \quad (23)$$

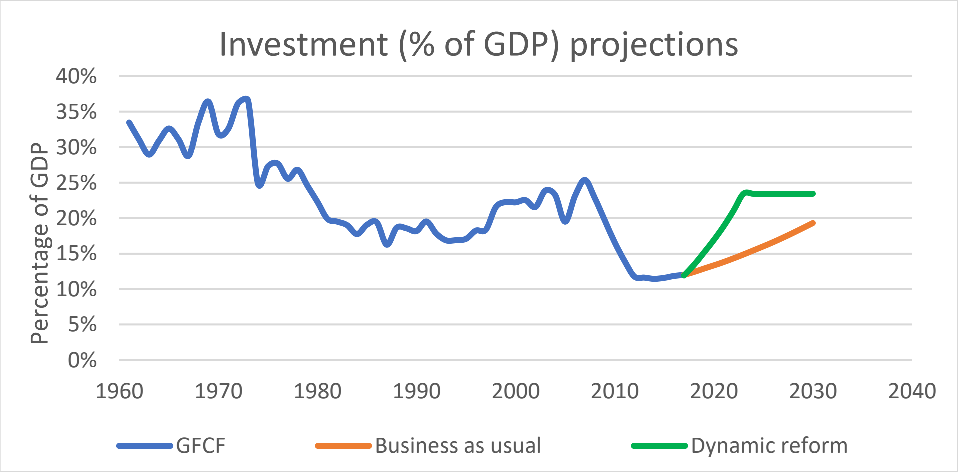

Figure 23: GFCF in GDP share of Greece from 1960 to 2017 and future scenarios.

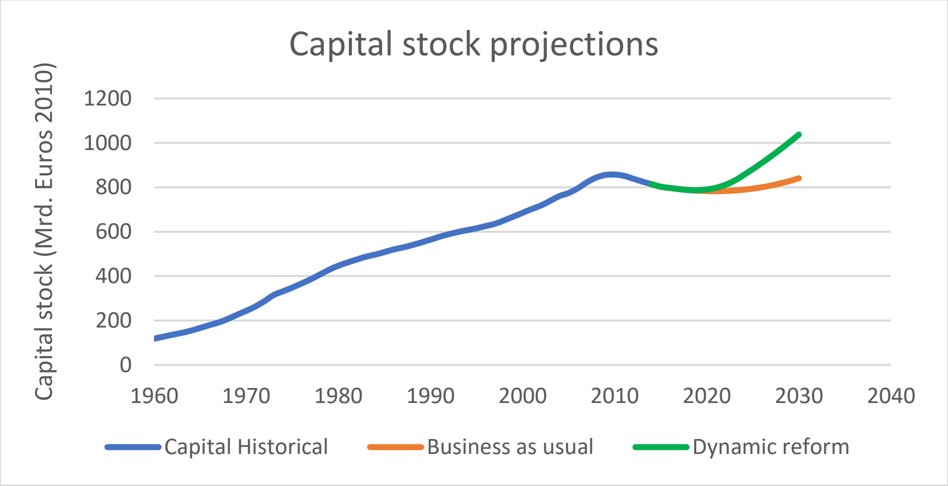

Figure 24: Future scenarios for capital stock of Greece until 2030.

3.2.2 Dynamic Reform scenario in Capital

According to the Hellenic Federation of Enterprises (SEV), Greece has the potential for a dynamic scenario, of doubling its productive investment, and reaching 20% of GDP three times faster than in the previous case. This could be achieved if the state manages to go through a reforming ‘big bang’. This means the implementation of reformations that would make the country stand out from the global investment competition, by making it friendly and appealing to industrial and technological investment. Furthermore, it would be meaningful to show interest in utilizing the capital, not only for the benefit of the national economy, but also for the benefit of the investors who are those taking risks. Mediums that would work towards this direction include reduction of bureaucracy and administrative stalling, reduction of licensing timeframe, corporate tax reduction and simplification of tax procedures, creating space for innovation and entrepreneurship, focusing on more medium and small business exporting, privatization and liberalization of a number of sectors, increase in private investment and proportional decrease in private consumption [44], [45].

Nevertheless, the introduction of such numerous reformations simultaneously, could potentially come as a shock for the existing national labor and business system, if not done properly and without the necessary foundation. It could even backlash and ultimately not bring positive results. For this reason, it would be essential to dedicate share of the total investment in public matters with emphasis to the sustain and reform of institutions, considering their progress slowed down during the years of crisis. For example, the increase in education funding and its constant modernization can help render workforce ready to catch up with the foreign progress easier, fight against corruption would make processes more efficient and some money blackholes could potentially be eliminated, while health system upgrade would also help establish healthier and more productive individuals.

In this optimistic case, considering that the trust of investors can be gained anew, the annual growth rate of investment could potentially be 15%. The monetary results of this assumption for the GFCF is also displayed in Annex Figure 19. This path shows fast rise of the investment which could vary around 60 € billion per year by the second half of the coming decade. In other terms, Figure 23 shows achieving the European average of 20% GDP share of GFCF, in less than 5 years. When creating this scenario, the percentages were purposefully kept constant after grasping pre-crisis values, to avoid further extreme estimations. As a result, similar to the procedure of the previous case and using eq. (23), the capital stock would develop as in the respective curve of Figure 24. It seems that after a few years of lag, Greece’s capital would finally start increasing quite rapidly, surpassing even the levels of pre-crisis times, and reaching as high as 1037 € billion in 2030.

3.3 Exergy efficiency scenarios

In this subchapter, two scenarios for the evolution of the second-law aggregate efficiency of Greece will be created. To do that first, the progress of the country towards meeting the climate goals of 2030 will be presented. Then, exergy analysis will be made for the most exergy intensive sub-sectors of the economy. Following, current related policies that are in place will be mentioned. Finally, based on this information, assumptions for use in the two new scenarios will be made.

3.3.1 Climate Goals for 2030

In compliance to the EU directive 2009/28/EC [46], Greece formed the National Renewable Energy Action Plan (NREAP) [47] in 2010, which set 4 goals until 2020 directly connected with the sharp increase of Renewable Energy Sources (RES) in the country's energy mix. These goals are: i) 18% of gross final energy consumption generated by RES (later became 20%), ii) 20% of heating and cooling consumption met by RES, iii) 40% of electricity consumption generated by RES and iv) 10% of energy demand in transport met by RES. Additionally, serving the common EU goal to decrease greenhouse gas (GHG) emissions by 20% (reference year is 1990) by 2020, and according to Decision No 406/2009/EC, Greece will have to reduce the non-ETS (buildings, transportation, agriculture etc.) emissions by 4% compared to 2005. Finally, in accordance to Directive 2012/27/EU the country set a target for energy consumption in 2020 not to exceed 24.7 Mtoe (primary energy) or 18.4 Mtoe (final energy).

In 2015, for each of the above RES related targets the achieved percentages were i) 15.4%, ii) 25.9% iii) 22.1% and iv) 1.4% respectively, while the non-ETS GHG emissions dropped to 44.5 from 61.78 Mt CO_2 eq, and primary energy consumption was 23.7 Mtoe. Specifically, the achievement of the targets on electricity generation and transportation are no longer feasible, as a result of the economic crisis and certain political choices that have hindered the RES potential in the electricity generation sector, simultaneously supporting fossil fuel. The initial target for RES in final consumption is considered feasible, however the more recent 20% is not. Note here that, despite the investment in RES the previous years, additional investment is needed even if the energy demand stays as low as the past few years. The limitation of GHG emissions of non-ETS and the RES target for heating & cooling have been achieved, yet this was mainly the result of reduction in economic activities rather than policy measures. The primary energy consumption measured is lower but still close to the boundary, so it is not considered as an achievement yet [48].

The main source of GHG emissions in Greece is the energy sector (energy generation and consumption), since during the last three decades, the emissions of the sector averagely amount to 75% of the total emissions. More specifically, the emissions from electricity generation pertains to around 50% of the energy sector emissions and 37.5% of the total emissions. Still, in 2015 the national emissions were just 6.6% lower compared to 1990. Despite the economic crisis, Greece has a poor climatic performance inside the EU-28 [48].

In the meantime, the international communities' efforts in the fight against climate change were intensified with the Paris Agreement in 2015. In the respective conference, the commitment was to adopt long-term goals in order to primarily limit the increase in global average temperature below 2°C compared to preindustrial levels, while simultaneously struggling to limit this temperature rise even below 1.5°C. Related to this matter, in 2014, the EC built the "Energy Roadmap 2050", aiming to further decrease GHG emissions and reform the energy sector until 2030. EC also specified the new crucial target of lowering the emissions in EU by at least 40% until 2030, compared to 1990 levels, with intervention in both the ETS (power and industry sector large scale facilities and aviation sector) and non-ETS sectors. Yet, this decision does not include national targets. Other EU goals are, the RES penetration by at least 27% in the gross final energy consumption by 2030, and the energy efficiency improvement at EU level by at least 30% in 2030 [48].

Greece is in an initial stage regarding the development of a national plan for the years 2021-2030, as a continuation to the current decade's plan (NREAP). A ministerial steering committee is planned to be formed and will be supported by technical working groups with the participation of different authorities, like the Ministry of Environment and Energy (YPEKA) and the Centre of Renewable Energy Sources and Saving (CRES). Thus, no concrete targets on renewable energy and energy efficiency beyond 2020 have been set yet [48], [49]. Nevertheless, regarding GHG emission in the non-ETS sectors, for Greece there is a mere requirement of 16% decline in 2030 compared to 2005 levels. Additionally, relevant to the 27% RES penetration in EU gross final energy consumption in 2030, a 50% of RES penetration in electricity generation is expected. There are no exact targets for Member States (MS) regarding the RES penetration to gross final energy consumption, but according to EC's Staff Working Document there are some indicative objectives, which for Greece range between 26% to 34% varying according to different scenarios (for the reference scenario it is 30%) [48], [50].

3.3.2 Analysis of important sub-sectors

With the purpose of improving the aggregate second-law efficiency of Greece, two things can be done: i) increase the second-law efficiencies of respective end uses (Table 2) and/or ii) change the share of energy carriers in favor of those that can be used in more efficient processes, e.g. electrical mechanical drive rather than diesel engines. However, when not assuming change in activities of the various sub-sectors, it is important to keep the UW shares of the end-uses relatively stable.

Having that in mind, first the aggregate efficiencies of the different energy sectors (Annex Figure 13) are taken under consideration. It is shown that nowadays, the lower efficiencies are of the Transport sector and of Other sectors, ranging between 15% to 20%, while the efficiencies of Industry and Energy industry own use are higher, ranging between 30% and 35%. Looking at Figure 7 as well, it can be seen that, Other sectors, Transport and Industry have the higher useful work shares of the total. Considering these findings, it would be beneficial to put more emphasis on improving the aggregate efficiencies of the first two less efficient sectors and secondarily also improve the other two industry sectors.

Moving deeper, it is essential to identify which sub-sectors in each main sector are the most UW intensive, in order to steer the focus on them. The useful work of these sub-subsectors for each of the main sectors of Other, Transport, Industry and Energy industry own use can be seen in Annex Figure 8, Annex Figure 9, Annex Figure 10 and Annex Figure 11 respectively. Because industry and energy industry own use have numerous sub-sectors, only the ones with the higher UW are shown. In Other sectors, the biggest UW shares are by far of the Residential flow and of Commercial & Public services, while Agriculture & Forestry comes third. In Transport, first place holds the Road transportation and second the Domestic Navigation. As far as the Industry is concerned, Non-ferrous metals and Non-metallic minerals are the most UW intensive, while Food & Tobacco comes next. Lastly, in the Energy industry, the most intensive sub-sector is the one of Oil refineries.

After recognising which sub-sectors produce the most UW[2] and could be addressed in order to have more substantial influence on the aggregate exergy efficiency, what remains is to pinpoint the primary energy carriers' products that are used in them in order to examine what margins for share change are available.

Regarding *Other sectors*, in the *Residential* sub-sector, electricity is by far the essential energy carrier, addressing around 70% of the total UW of the sub-sector in the recent years, and is used for all daily activities such as mechanical drive, cooking, heating, cooling, lighting and for all electrical and electronic devices. Then, comes diesel oil used for space heating (Fuel – LTH 50°C), which has dropped significantly the last years, to 10.5% in 2014, followed by primary solid biofuels (wood, pellets etc.) used for heating (Fuel – LTH 50°C) at 8.6%. Natural gas used mainly in heating (Fuel – LTH 50°C) and cooking held a much smaller share at 2.8%. Very small shares of UW hold also the heat from CHP and Solar thermal (CHP – LTH 50°C). In the *Commercial and Public Services* sub-sectors, the vast majority of UW is attributed to electricity, which held 92% in 2014, and generally is used for mech. drive, lighting, cooking, heating, cooling and all related devices. Lastly, in *Agriculture & Forestry*, electricity had in 2014 the biggest share of around 80%, LPG for stationary mechanical drive stood for almost 13% and primary solid biofuels for low temp. heating (Fuel – LTH 90°C) had 5.4%. Strangely, diesel oil for vehicles which until 2010 held the highest share above 40%, in the end of the series, it has almost disappeared to less than 1%. This might be due to flaw of the database or lack of data.

Regarding *Transport*, the means of *Road* conveyance use primarily gasoline with 48.4% and secondarily diesel with 43.9% share, in 2014. Small shares had LPG vehicles at 4% and biodiesel vehicles with 3.2%. Electricity as a vehicle energy carrier accounted for just 0.3%. In the *Navigation* sub-sector, diesel oil and fuel oil attributed for the almost total of UW, having 57.4% and 42.4% shares respectively.

Regarding *Industry*, in the *Non-ferrous metals* sub-sector, in 2014 electricity alone held the majority of UW produced at 55% share, serving all uses such as mech. drive, heating, lighting and other electric uses. Second came natural gas for high temperature heating processes (Fuel – HTH 500°C) with 35% and last was the use of bituminous coal for medium temp. heating processes (Fuel – MTH 150°C) at 7.4%. In the *Non-metallic minerals* sub-sector, the electricity share was 20.6%, while petroleum coke

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[2] Notice here that when electricity is mentioned, it considers the summed UW of all four functions (categories) it may be produced in every sector, as mentioned in subchapter 2.1.3.4. Namely, it accounts for mechanical drive, heat, other electric uses and light.

for medium temp. heating (Fuel – MTH 150°C) held 53.2%. Other widely consumed fuels where bituminous coal at 14.1% and natural gas at 5.8%, necessary for high temp. heating processes (Fuel – HTH 500°C). Diesel oil was used for stationary mech. drive with 3% UW share. Moving to the *Food & Tobacco* sub-sector, electricity was again first holding almost 65% of UW, then primary solid biofuels held the share of 11.7% for low temp. heating (Fuel – LTH 90°C) and following came fuel oil, natural gas and LPG having smaller shares for the same end use.

Regarding *Energy sector own uses*, the *Oil refineries* sub-sector in 2014 used primarily fuel oil, refinery gas and petroleum coke for medium temp. heating processes (Fuel – MTH 150°C) with 33.43%, 31.18% and 22.7% respective shares of UW produced. Electricity accounted for just 9.7%.

Overall, it was identified that, for a lot of activities and processes related to heating mainly fossil fuels are burned, using primarily conventional technologies (Fuel – L-/M-/HTH). Thus, it would be advantageous to change the energy carriers towards others less polluting and/or use CHP technologies, where they are available, since they have better 2nd-law efficiencies.

Additionally, looking at useful work from another point of view, previously it has been identified that *mechanical drive* is by far the category with the highest UW share (Figure 6). From further analysis in the MD category, it was recognised that, in year 2014, the bigger shares of final exergy were injected in MD related to gasoline and diesel vehicles (Annex Figure 21). However, their respective shares of UW were much lower, while first were the shares of electricity produced MD (Annex Figure 22). As an induction, improving conventional vehicles efficiency or and/or shifting to EVs would be of great benefit.

3.3.3 Policies

The 4th National Energy Efficiency Action Plan of Greece [51] provides all the existing and new policies that aim primarily towards improving the overall energy efficiency of the country and decreasing energy consumption and GHG emissions. Subsequently, the related measures can reduce energy costs for consumers, contribute to the safety of energy supply, boost competitiveness, help towards sustainability of the economy and create jobs. Overall, they support the energy transition and growth of the country through the current harsh environment. Below are given various measures of the Plan in the different sectors, which are currently being implemented, or will in the future, and are relevant to the analysis of this work.

In the *residential sector*, according to a regulation, it is mandatory to install solar thermal systems in new buildings since 2011. Financial incentives are offered for replacing oil-fired with gas-fired heating systems as well as for upgrading the energy efficiency of existing heating and cooling systems since 2017. Usually these funding comes from the European Regional Development Fund (ERDF). There is also a regulation for improving the overall energy performance of buildings through inspections, studies and classification.

In the *services sector*, it is mandatory to install solar thermal systems in new buildings since 2011. Financial incentives are given for improving the energy efficiency of SMEs through lighting, electric installations and heating system upgrades since 2018. More specifically, the *public sector* is expected to show an exemplary image in the future. Regulations render it mandatory to improve low efficiency light fittings, since 2006, and to install central solar thermal systems for hot water requirements, since 2011. An EU grant, since 2018, is aiming the energy upgrading of public buildings by changing boilers, burners, air-conditioners and solar systems with more efficient ones. It also aims the construction of CHP facilities for self-consumption as well as RES technologies purposed for cooling. Moreover, from 2019 onwards all public building should be nearly zero energy buildings (NZEBs) [52]. These targets are justified, considering the size of the public sector is big, as explained in 2.2.1.

In the *transportation sector* there are a few measures in progress that could make a difference in the future. These concern financial incentives or the replacement of private vehicles and the promotion of energy-efficient vehicles (biofuel vehicles, hybrids) (2009). Another is the introduction of electric vehicles (EVs) and respective charging points (2014).

Regarding *industries*, the Plan has an existing policy aiming to support the improvement of energy efficiency in manufacturing enterprises with financial incentives since 2015, but it has not been implemented yet. However, a similar policy started in 2018 aiming to improve the efficiency of manufacturing processes for SMEs of the sector.

In general, grants, among others, are promoting the construction of CHP in hospitals since 2011, and the installation of district heating networks for residential use since 2011 and 2018. The use of heating/cooling systems based on RES and the use of CHP in industries, services, tourism and shipping is funded since 2018 as well.

3.3.4 Scenarios

The past decade, Greece went through a prolonged period of reduced economic activity with reduction in incomes. As a result, big changes in the energy behavior of households and businesses took place. Specifically, an important share of residential buildings does not achieve suitable thermal comfort conditions, especially in winter.

The expected growth assumed in this work can eventually improve the economic status of households and enterprise performances, and generally improve living standards. Yet, the application of energy savings measures usually needs available capital. The question is whether a better financial status will lead people and entities to realize the investments needed, resulting in conservation of energy, or will it push them to improve their living standards way more, resulting in irregular increase of energy consumption (rebound effect). Under the scope of this thesis, the tendency towards the former path will be considered.

The following exergy efficiency scenarios will follow the framework of two scenarios for the energy system which were created by WWF Greece [48].

3.3.4.1 Business as Usual in energy efficiency

In this scenario the evolution of the energy system will follow the already implemented and agreed upon decisions and policies. Large instalment of different RES technologies is expected to support the energy system. Nevertheless, the lignite thermal power plants will continue playing an important role, with a new unit constructed, another upgraded and numerous units closing down until 2030. Energy storage systems will be built, anti-pollution technologies will be equipped to old lignite units and interconnections both cross-border and between the main grid and Aegean islands will be built.

The application of the energy saving policies and measures, associated with the final consumption sectors, is briefly supported by a mild economic growth. The majority of population, being preoccupied with satisfying other necessities, stays rather uninformed and insensitive in respect to the need for energy transition. Thus, the implementation of measures is modest, it requires low investment costs and can be realised when generally incomes are limited. The main assumptions are:

Penetration of modern and more efficient devices, equipment and machines in all the sector of the economy, however in small scale. This will lead to mild linear increase of the 2nd-law efficiencies of the end-uses (Annex Figure 23), similar to past decades. The development of the exergy efficiencies is based on manipulation of estimates given in the EU Reference Scenario on the path leading to 2050 [50].

In *Other sectors*, by 2030, most of the changes in energy sources UW shares will happen related to LTH (50°C) uses, e.g. space and water heating. A small increase is assumed in CHP and geothermal technologies (CHP – LTH 50°C), rising up to <1.1%. Solar thermal system development is more focused, reaching a bit higher shares up to <4% of the UW produced, especially in the service sector. This is driven by the government regulations and the small financial incentives. Simultaneously, burning of fossil fuels (e.g. diesel oil, charcoal) as well as use of electricity for heating, will decrease respectively. Moreover, residencies will continue shifting gently from diesel oil use to natural gas, since NG is becoming more accessible throughout the country and is less polluting. The services of traditional biomass will be slightly limited as well. Regarding stationary mechanical drive, small shift of ≈1-1.3% from LPG towards electricity is expected. A small increase towards other electric uses will also take place because electronic appliances are increasingly getting involved in all daily activities. These electricity related changes happen following the broader electrification and automation era in Europe.

In *Transport*, the use of gasoline (gasoline vehicles) and diesel oil (diesel vehicles) for road transportation will decrease briefly to 46% and 40% respectively, in order to promote biofuels, giving shares of 4% to biogasoline and 4% to biodiesel as well. Because of an assumed weak promotion of EV policies and limited installation of their charging stations, electricity will just reach 2% of the total road UW, by 2030. In the rail related transportation, even though it is not a very UW intensive sector, changes are expected to happen in the near future. Specifically, following the upcoming introduction of purely electric trains in the railway network of Greece, electricity's UW share (diesel-electric end use) will increase to 50%. Biodiesel's share is also assumed to continue growing up to 5%, leading diesel oil to drop to 45% of UW generated. In the domestic navigation sub-sector, diesel and fuel oils will decrease briefly, to give a small space for the use of biodiesel (1% of produced UW).

The *Industry* sector, apart from having certain policies to regulate it, needs to be more efficient because its driver is global competition. Furthermore, industries have to lower their GHG emissions following the EU regulations. In respect to that, the non-ferrous metals sub-sector will partly reduce the conventional combustion of fossil fuels, e.g. sub bituminous coal, used in MTH (150°C) processes, to give room for the entry of CHP (150°C) heat as 2% share of UW production, by 2030. This is assumed to be a similar case for the non-metallic minerals sub-sector, where heat MTH (150°C) from CHP is going to increase up to 4%. Solar thermal installations for LTH (120°C) processes are expected to take place as well, leading the respective share of UW to 1%. Also, a small shift of 1.2% from coal products used in HTH processes (500°C) to natural gas is considered. In the Food & Tobacco industry, a small transition from fuel oil to natural gas, and also the introduction of plants for the production of biogas and biodiesel, are assumed.

In the *EIOU* sector, the oil refinery sub-sector is the largest as for UW produced. Its use in fossil fuels for MTH (150°C) processes produced more than 80% of the UW in 2014. Therefore, it is considered important to transfer a small fraction of them, of about 7.5%, to CHP MTH (150°C) technologies, by 2030.

All the important changes in product UW shares can be found collectively in Annex Table 3.

Lastly, because of the mild economic improvement, the *Industry* and *Transport* sectors are considered to increase by 1% of the total UW produced in the economy, while the *Other sectors* is considered to decline by 2%, until 2030. This is assumed, considering a small tendency of these sectors to move towards their past shares (Annex Figure 25). The *EIOU* is considered to keep the shame share, on this and the next scenario. The share of muscle work produced from people and working animals is going to briefly decline, following to the population decrease of Greece.

3.3.4.2 Enhanced Energy Efficiency

This scenario differs from the previous one in the sense that more ambitious energy saving policies are implemented in the final consumption sectors (promoting higher efficiency equipment, electrification of vehicle fleet etc.). This optimistic course is following a faster growth, thus enabling more players to get involved. People start developing a new mentality and become more motivated to embrace changes leading to a “greener” future. Generally, more expensive investments are made and eventually more significant efficiency improvements are to be achieved. The main assumptions are:

Bigger scale penetration of modern and more efficient devices, equipment and machines in all the sectors of the economy, leading to higher increase of the 2^{nd}-law efficiencies of the end-uses (Annex Figure 24). The development of the exergy efficiencies is based on manipulation of more optimistic estimates of the EU reference scenario [50], compared to the previous case.

In *Other sectors*, the commitment to promote RES and CHP technologies for water and space heating is higher and related measures are promoted anew. This is driving the shares of UW produced by solar thermal (CHP – LTH 50°C) up to >8% in 2030. Simultaneously, there is further limitation of diesel, traditional biomass and electricity use for heating in the residential sub-sector, compared to the previous scenario. On the contrary, the service of natural gas increases to 7.3% of the total UW. Even less LPG will be used for stationary MD, and more MD from electricity will be produced instead.

In *Transport*, the necessity to include biofuels in road transportation leads biodiesel and biogasoline to reach 6% of the total UW generated each, while gasoline declines at 40% and diesel at 38%. The effort to electrify transportation is more intense, by introducing electric buses and giving more incentives to buy EVs. Eventually driving electricity as an energy carrier to 6% of the UW by 2030. The same trend pushes electricity in rail transportation even higher, to 55%, while biodiesel climbs at 8%. In domestic navigation, there is the introduction of CHP technologies, occupying 5% of the total UW produced, while biodiesel increases to 2%.

In *Industry*, the combustion of coal and coke products for MTH (150°C) processes is restricted more dynamically, in order to limit CO2 emissions more drastically by 2030. Instead, the shares of UW produced from CHP (150°C) technologies is going to range between 5-10%, in the non-ferrous metals and non-metallic minerals sub-sectors. Additionally, biodiesel for HTH (500°C) processes will be introduced to take the share of 2.2% of UW in the second sub-sector mentioned. The service of natural gas is also going to increase further to 11% of UW produced for HTH (500°C) processes. Similar shift towards natural gas is assumed to take place in the Food & Tobacco sub-sector, reaching 11% of UW generated. Also, the introduction of biodiesel and biogases is going to be larger, giving them 3% and 2% shares of UW by 2030 respectively.

In *EIOU*, the service of fossil fuels for MTH (150°C) processes in the oil refining industry is assumed to decline significantly, allowing the respective temperature CHP technologies to acquire a share of >13% of the UW produced by 2030.

All the important changes in product UW shares can be found collectively in Annex Table 3.

Finally, in this scenario, because of more rapid growth, the UW shares of *Industry* and *Transport* from the total are assumed to grow by 1.5% each until 2030, while the *Other sectors'* share is going to decline by 3%.

3.3.5 Projections of aggregate efficiency

After making the necessary assumptions, the next step is to estimate the aggregate final-to-useful exergy efficiency of Greece for the two scenarios. To do that, eq. (24) was conceived and used.

$$Agg.Eff_{y}. = \frac{1}{\sum \frac{UW_{ecp,y}}{UW_{sub-sector,y}}(\%) * \frac{1}{\varepsilon_k} * \frac{UW_{sub-sector,y}}{UW_{sector,y}}(\%) * \frac{UW_{sector,y}}{UW_{total.y}}(\%)} \qquad (24)$$

All the percentages started based on 2014. The ones changing did so linearly until 2030, while the rest remained the same. The shares of energy carrier products inside their respective sub-sector, the 2nd-law efficiency of the different end uses ε_k, as well as the shares of sectors from the total, are based on the assumptions mentioned in the two scenarios. The shares of sub-sectors in sectors remained the same throughout the whole 2014-2030 period.

Ultimately, the projections for the country's aggregate efficiency are presented in Figure 25 where it is shown that both scenarios bring significant improvement. Namely, the first scenario (BaU), is leading the efficiency to increase from 20.07%, in 2014, to 22.41% in 2030, when the second more optimistic scenario (EEE) is accomplishing twice the gains, with 24.97% efficiency in the end of the period. These results show that, the application of the assumed measures can help overcome the stagnation in efficiency observed during the previous decades and eventually cause improvement in rates similar to those observed between 1970 and 1980.

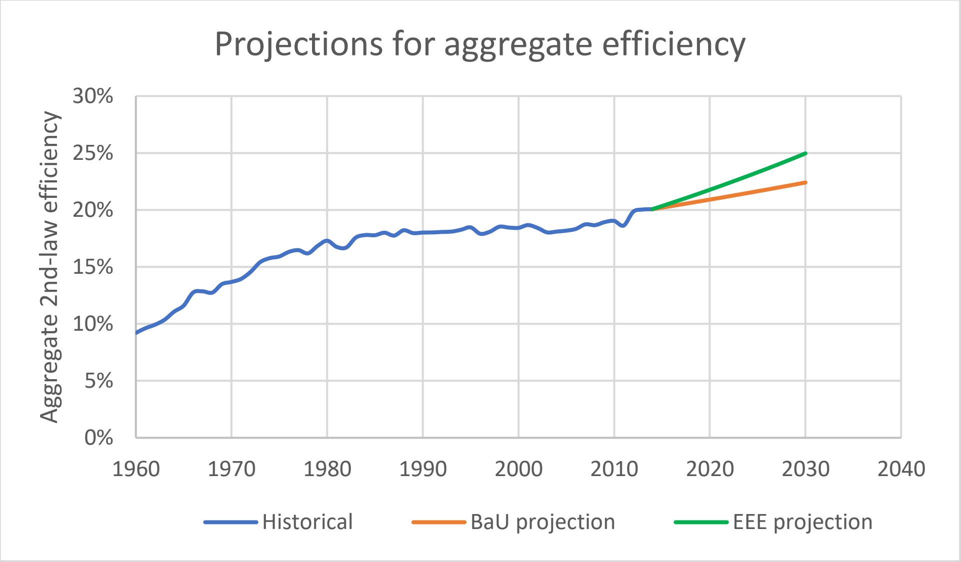

Figure 25: Future projections for the aggregate 2nd-law efficiency of Greece, 2015-2030.

The respective aggregate efficiency of each of the main four sectors can be seen in Annex Figure 26. It is observed that for both scenarios, the applied measures benefitted mostly the EIOU sector, and then followed Industry, Transport and Other sectors, with this order. This comparison is made by means of absolute difference in efficiency values, in each sector, between 2014 and 2030. When comparing in growth terms, then chiefly benefitted was Transport, and then follow EIOU, Other sectors and Industry.

When looking the broader picture, these rises in domestic efficiencies could also contribute towards the common goal of increasing the overall efficiency in EU level, which is stated earlier.

3.3.5.1 Projections of TFP

In order to estimate future economic growth, besides having projections for labor (L) and capital (K), also the future development of TFP is required.

To forecast the real TFP, first the projections of Greece's aggregate final-to-useful exergy efficiency were used in eq. (22), like in subchapter 2.2.4, in order to calculate the future indexed TFPs. The outcome was two different indexed TFP development trends, each for one of the two energy efficiency scenarios, and the results are shown in Annex Figure 27. From these trends, the annual growth rates of TFPs were computed, being approximately 0.73% for BaU and 1.44% for EEE. Then, the growth rates were applied in order to develop the real TFPs curve from 2014 to 2030. Note that, for the first year of the projections, meaning 2015, the same value as in 2014 was used, in order to avoid a potential "jump" when transitioning from the last historical to the first projection.

Finally, the real TFP projections for the two energy efficiency scenarios are depicted in Figure 26. In one case, the results show that for the "business as usual" scenario, total factor productivity increases moderately in the future, being able to just reach as high as the pre-crisis levels, by 2030. In the other case, as expected by the more optimistic scenario, the TFP is growing faster, surpassing by the end of the examined period the peak it met in 2007.

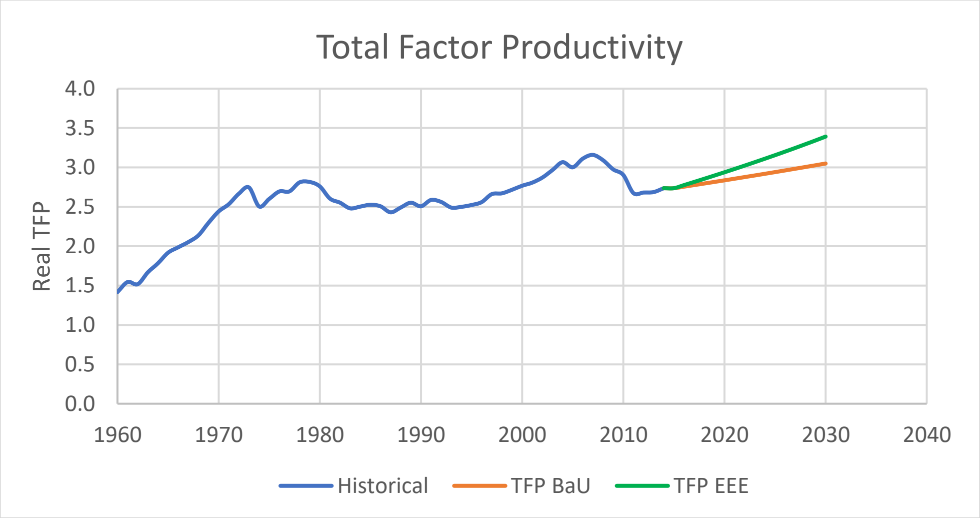

Figure 26: Real TFP projections for the two efficiency scenarios of Greece, 2015-2030.

Chapter 4

Final Projections

In this chapter, the final projections for the economic growth of Greece, as well for the total useful work and final exergy will be made, based on the two scenarios of combined factors. To do that, one complete scenario will consider mostly mild development or stagnation in the different factors that influence the economy, while the second will consider more radical changes. Then using the model proposed in MEET2030, estimations for the GDP up to 2030 will be made, and according to this, useful work and final exergy will also be calculated. This way, two extreme cases for the country's future development are anticipated and the results will be compared and discussed.

4.1 Economic growth

To estimate the economic growth of Greece, it is necessary to combine the previous scenarios on labor, capital stock and TFP (which is linked to exergy efficiency). On one hand, the pessimistic scenarios from the three factors were coupled together in one main scenario. Mild growth would keep unemployment higher, investment in capital would be limited, compensating by a big fraction for its depreciation throughout time, and consequently, less money would be available for improvements of efficiencies, all connected in a vicious cycle. This main scenario will be called "Business as Usual" (BaU). On the other hand, the optimistic scenarios of the same factors were coupled in a second main scenario. Greater investments would bring higher returns, faster economic growth would be expected, more employment would be possible, and eventually more wealth would be available for increasing efficiencies in all sectors. All components working in harmony, like a well-oiled machine. This main scenario will be called "Metamorphosis" (Meta).

The projections of gross domestic product for Greece were made using equation (20). These estimations associated with the pessimistic and optimistic groups of assumptions are presented in Figure 27. As expected, Meta predicts a faster growth of GDP for Greece, reaching the value of 277 € billion in 2030, much higher than the outcome of BaU, which only arrives at 222 € billion. Also important is the trend of the projections. Both trends look like straight lines, which is probably because, the concave trend of labor projections and the convex trends of capital stock projections counteract with each other.

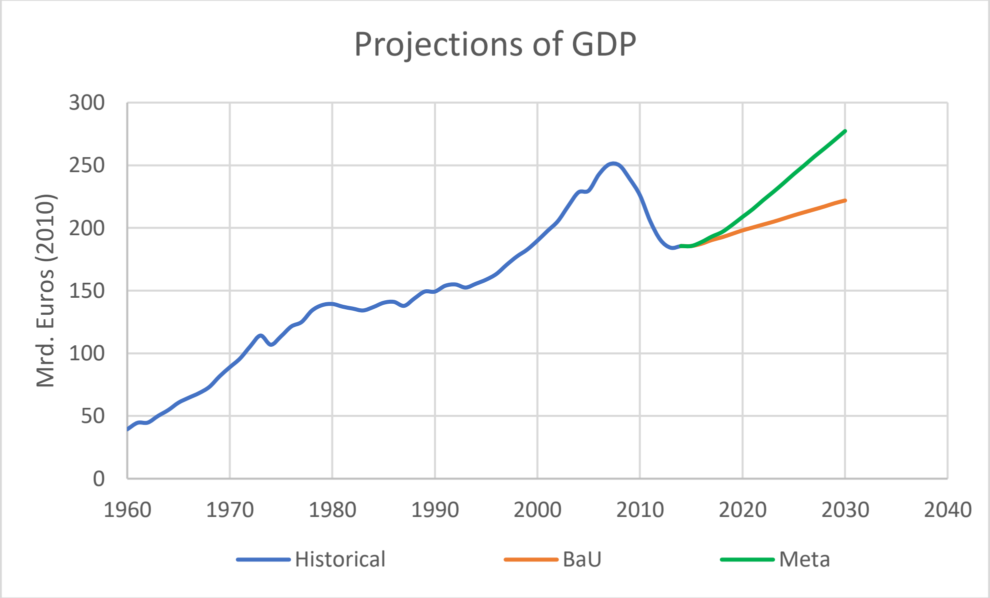

Figure 27: Projections of GDP for Greece, 2015-2030.

Taking a closer look, in the pessimistic scenario, the annual growth rates of the last 12 years of projection oscillate roughly between 1% and 1.4%, with 1.2% average. This growth average could be likened to the one of the period 1986-1995, when Greece started advancing from the stagnation it occurred before. This is not an ideal scenario as the development is slow and will probably preserve the lack of competition and hinder progress in most sectors. Still, the country could function in the tail of EU.

In the optimistic scenario, annual growth rates vary between 2.5% and 3.2%, with an average of 2.9%, very similar to the period between 1993 and 2002, when the country started growing its economy considerably, for the first time after the regime change. In this path, Greece could achieve the comeback it needs, show it has the potential to excel in different sectors, and try to be part of the forefront in Europe. The likelihood of this scenario is low, but it is still a plausible scenario, if strategic policies are introduced and the right measures are implemented strictly. Though, it is equally important not to repeat the mistakes of the past.

Something, that is generally desirable for an economy, is to have a relatively constant, positive growth. Nevertheless, if this growth is very high, it might lead to creation of “bubbles”, shocks in the economy, real estate issues, etc. The present scenarios do not lead to excessive growth rates, so a steady and safe economy development could be expected.

Moreover, in the frame of this current thesis, these two extreme projections of GDP are boundaries of a range in which the economic growth could potentially maneuver in the future. Regarding labor, this factor is more or less defined by population projections. Therefore, the challenge would be to make the right, strategic moves in order to trigger the necessary capital development, which in turn can enable more dynamic efficiency improvements. This way the advance of economic growth could be closer to the upper limit of these GDP projections, and consequently, benefits for the society can be greater.

4.2 Exergy

Having assumed future shares for useful work in the scenarios, it is also necessary to estimate UW in absolute values. In order to do that, the concept adopted in MEET2030 was used, which implies constant correlation between UW and GDP.

To proceed, the useful work intensities found in sub-chapter 2.2.3 and presented in Figure 16 were consulted. Considering the entire time series, the average UW intensity is 0.73 MJ/€, based on euros of 2010. However, the first years of the series, the intensity was increasing, and only after mid-1980s, it started oscillating above 0.8. As mentioned earlier, the index increases in economies while they are getting industrialized and then it starts becoming more constant, and Greece seems to be past that point. Additionally, as shown above, the economy in the two scenarios is expected to develop with growths similar to those during last three decades. For these two reasons, the average of the last 30 years for the useful work intensity is going to be assumed, which is 0.86 MJ/€. This intensity is not close to 1 MJ/€ (unlike when based on euros of 2000), as in the MEET2030 study, so there is no justification to use ‘1’ for the case of Greece.

Having said that, projections for useful work are made by using eq. (25), and the outcome is shown in Figure 28.

$$UW_y = GDP_y * 0.86(\frac{MJ}{€}) \qquad (25)$$

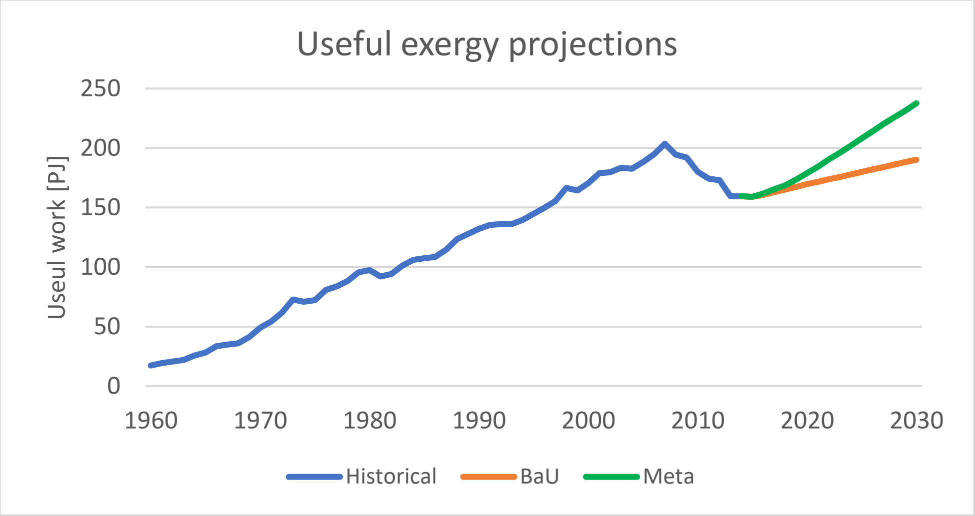

Figure 28: Useful work projections for Greece, 1915-2030.

As expected, the total useful work produced in the Meta scenario, related to enhanced energy efficiency and leading to a faster economic growth, is reaching levels much higher than in the past. The resulting value is 238 PJ in 2030. Regarding the BaU scenario, with the smaller improvement in efficiency, and consequently lower GDP growth, the total useful work increases as well, but with smaller rate, and arrives at pre-crisis levels.

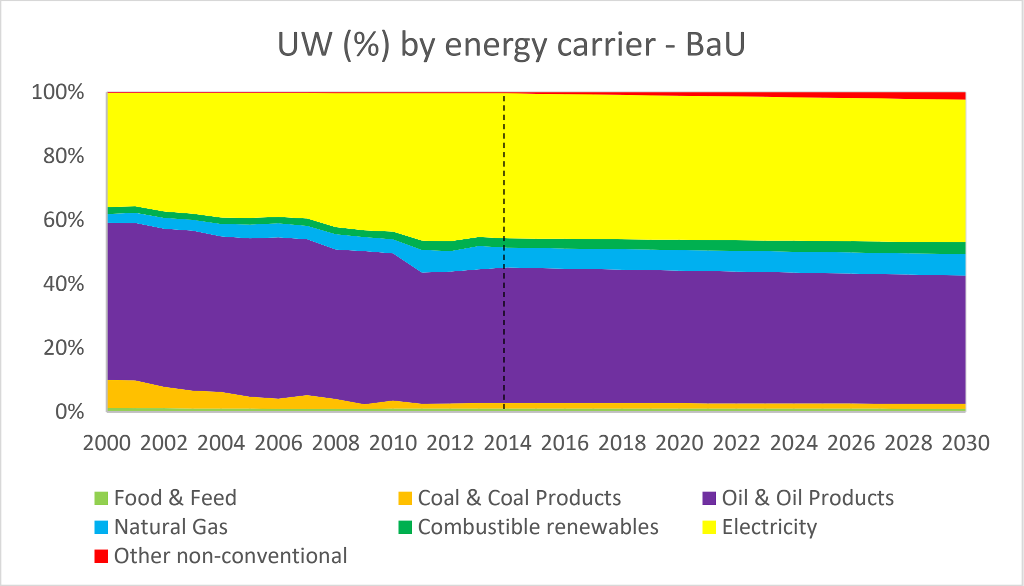

Figure 29: Projections of energy carrier share of UW for BaU, 2015-2030.

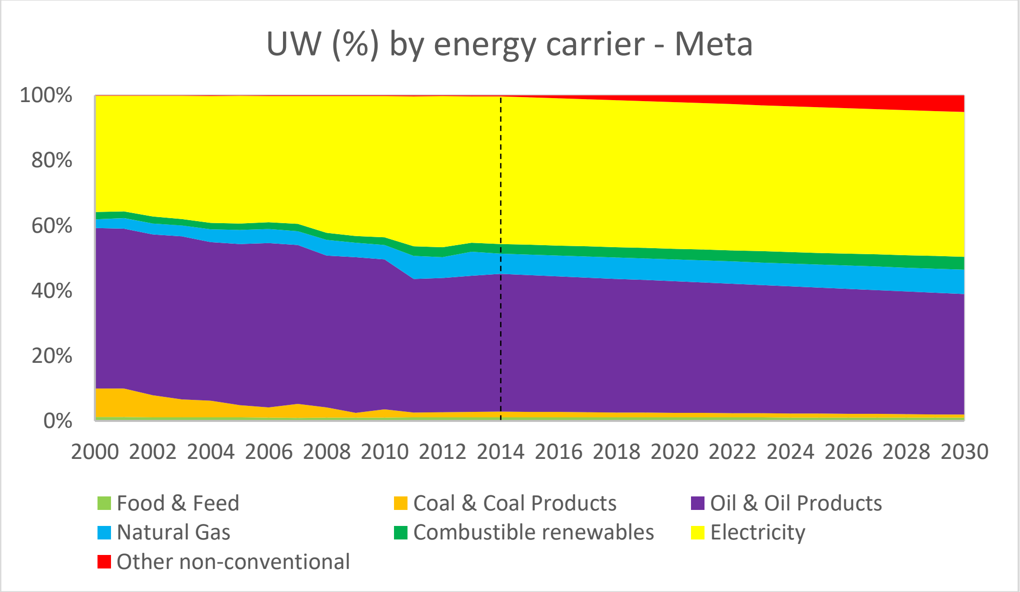

Figure 30: Projections of energy carrier share of UW for Meta, 2015-2030.

Regarding the shares of UW occupied by different energy carriers in the future, they can be seen in Figure 29 for BaU and in Figure 30 for Meta. In BaU, there is mainly a small decrease in oil products and a small increase in other non-conventional carriers (because of solar thermal and CHP technologies). In Meta, there is a significant decline in oil products and small decrease in electricity, while small increases in natural gas and combustible renewables are forecasted. Also, an important increase in other non-conventional carriers is expected. Regarding the shares of UW by end-use, they remain almost constant for both cases, as aimed from the beginning.

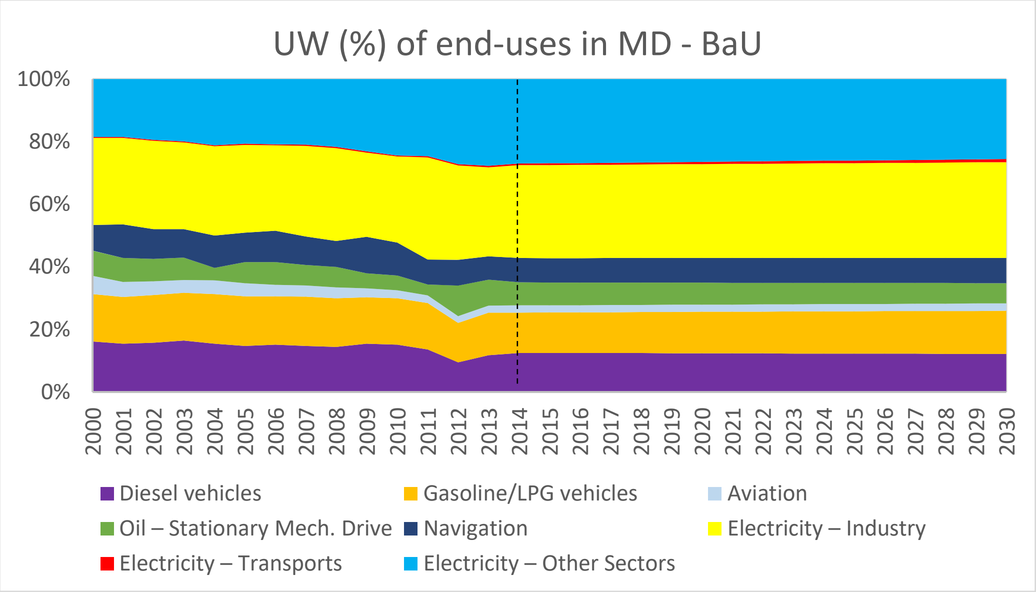

Figure 31: Projections of end-use share of UW in MD for BaU, 2015-2030.

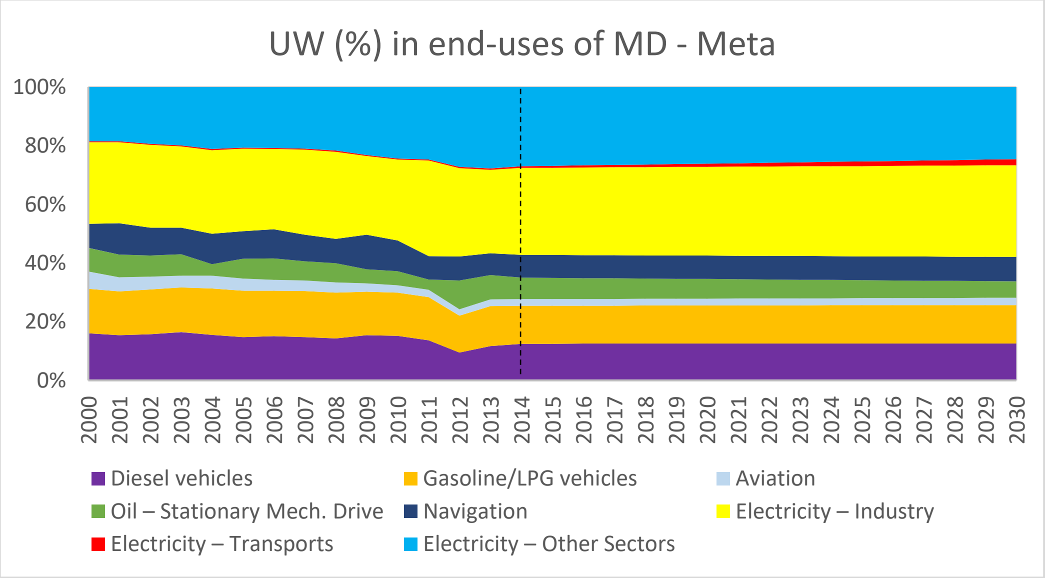

Figure 32: Projections of end-use share of UW in MD for Meta, 2015-2030.

In particular for mechanical drive, the shares of UW of its end-uses (Figure 31, Figure 32) stay roughly stable. Small exception is electricity for transportation that gains about 1% and 2% share, for BaU and Meta respectively, at the expense of electric MD in Other sectors.

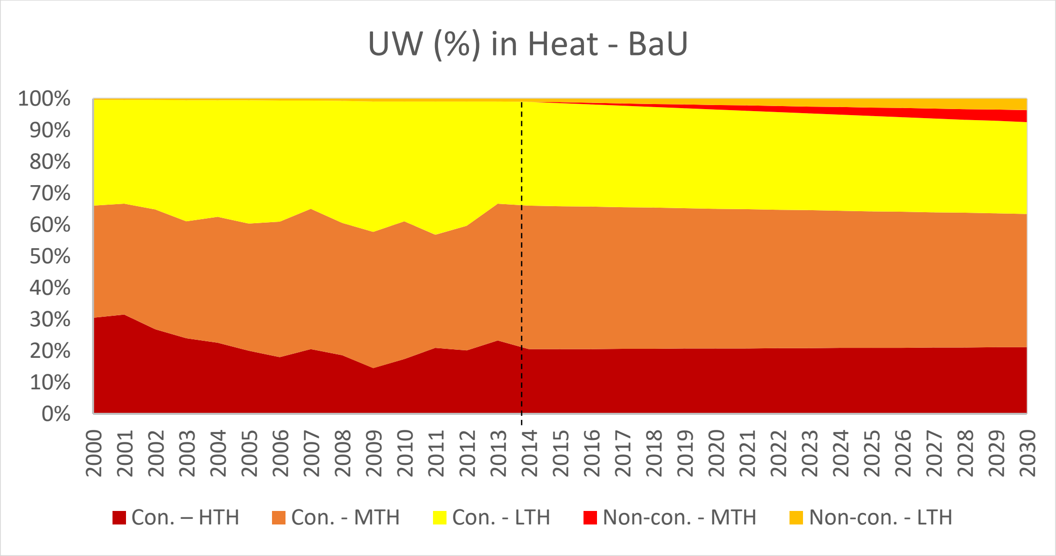

Figure 33: Projections of heat category share of UW in heating for BaU, 2015-20130.

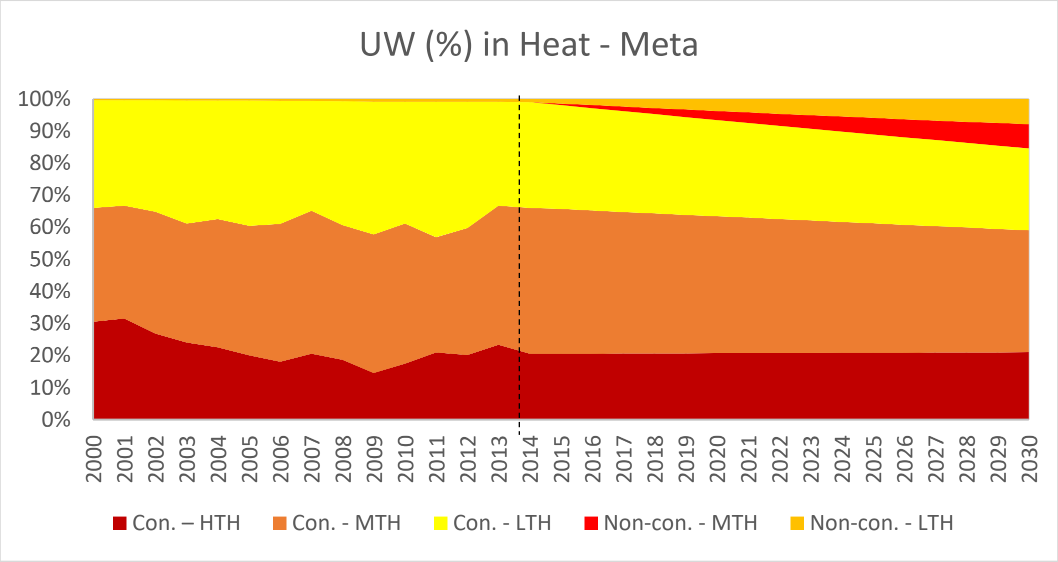

Figure 34: Projections of heat category share of UW in heating for Meta, 2015-20130.

As far as heating is concerned, UW shares of end uses by category (H- /M- /LTH) can be seen in Figure 33 for BaU, and Figure 34 for Meta. The HTH share of UW stays constant, since there is only one mapped category that can accommodate it (Fuel – HTH 500°C). However, the conventional technologies (fossil fuel / biomass burning and heating from electricity) used for MTH and LTH processes, give room for non-conventional processes (solar thermal, CHP). This results roughly to <4% for BaU and <8% for Meta, for each temperature category.

Next, it would be of interest to estimate also the total exergy injected for final consumption in the country. To do that, eq. (19) was used for the future years, and the resulting projections for final exergy are shown in Figure 35.

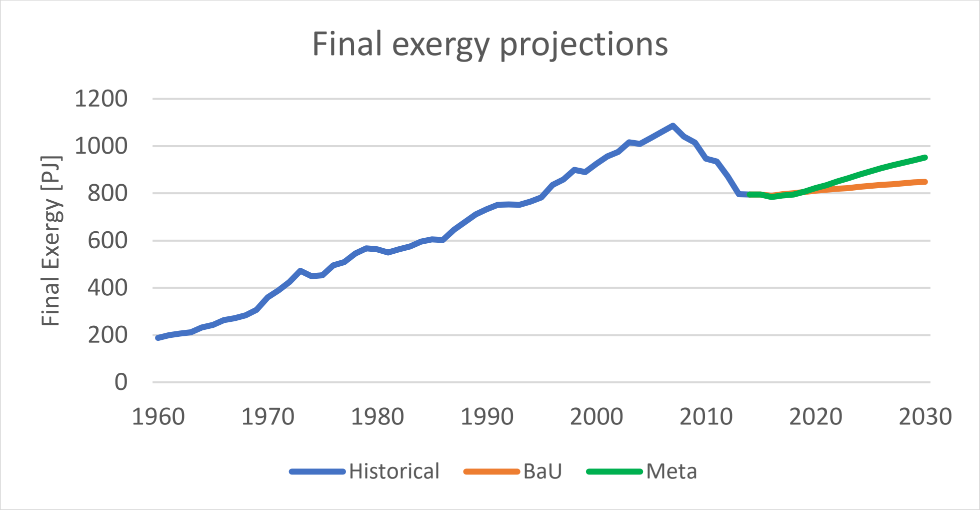

Figure 35: Final exergy projections for Greece, 1915-2030.

The final exergy in both scenarios is increasing, since the UW needed to drive growth is rising as well. However, because of the assumptions taken and the constant improvement of the aggregate exergy efficiencies, the rate of increase in FEx is smaller than in UW and GDP. This difference in growths is bigger for the Meta scenario. Finally, the final exergy arrives at 952 PJ for Meta, and at 848 PJ for BaU. Nevertheless, this change in relation between FEx and growth can also be interpreted into reduction of the amount of final exergy needed to produce a unit of GDP, i.e. final exergy intensity. Consequently, conservation of final and primary is promoted as well.

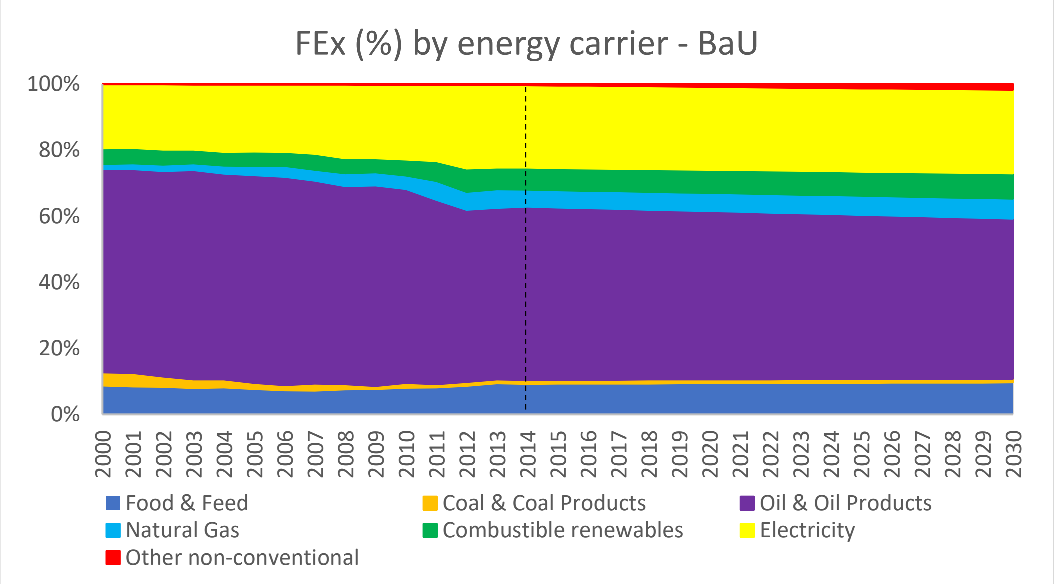

Figure 36:Projections of energy carrier share of FEx for BaU, 2015-2030.

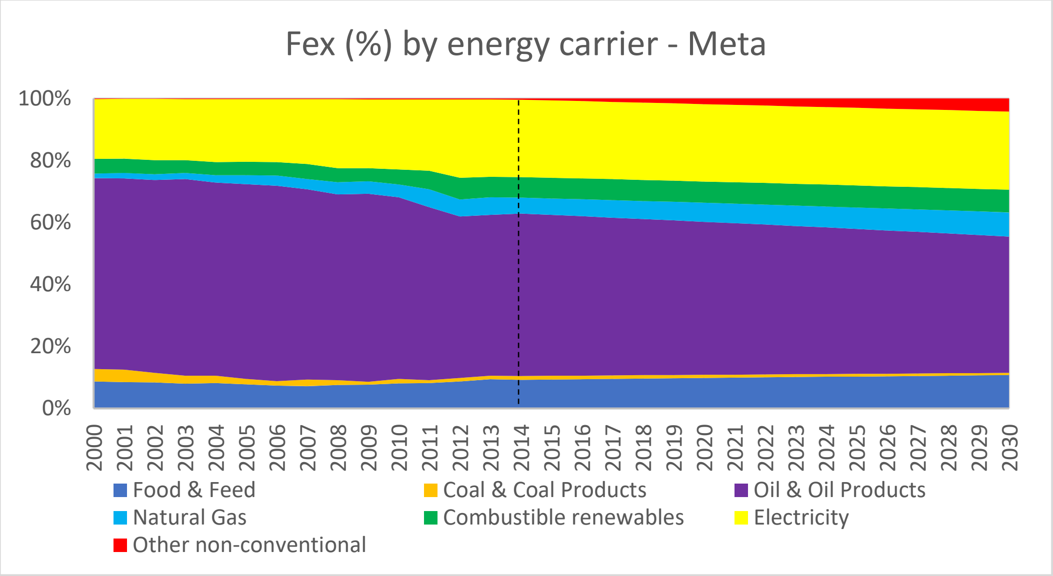

Figure 37: Projections of energy carrier share of FEx for Meta, 2015-2030.

Another important point is the evolution of energy carrier shares of Fex in the future. In BaU (Figure 36), there is a small decrease of oil use, around 4%, while its place takes natural gas, combustible renewables, electricity and mostly other non-conventional carriers. In Meta (Figure 37), the limitation of oil products is stronger, about 8.5%, and instead there is higher increase in the use of natural gas and mainly other non-conventional carriers.

This last finding can be translated in two things. First, the decrease in oil products use would render Greece less energy-dependent on related imports, since biofuels and electricity from RES could be produced domestically. Secondly, these findings, in combination with the GDP forecasts, imply that by using less polluting energy mix for the four main economy sectors, there is potential to decrease the dependency on fossil fuels for generating wealth. Consequently, this would help to partly mitigate GHG emissions. These additional benefits are of course more intense in the optimistic scenario.

4.3 Further discussion

To examine the environmental sustainability of these scenarios, in respect to the goals/restrictions of EU, also the development of energy trends and emissions in CO_2 equivalent would be necessary. In this thesis, this forecast is not happening because of time constraints. Yet, the calculation of energy and emissions, for the current scenarios, is suggested as possible future work. If the present scenarios do not lead to the required limitations in energy use and emissions, then a third scenario with more intensive energy transition assumptions and higher investment for energy saving measures, could be formulated.

Having touched the matter of European-level restrictions, it is meaningful to recognize that all EU countries are expected to function and develop under a common set of rules. Nevertheless, these rules sometimes might not serve all member states the same, when they have certain individual objectives. For instance, the faster recovery of the Greek economy is desirable, in order to try and catch up with the development that could have occurred, if the crisis consequences were not that vast. Yet, this has to be done with simultaneous compliance to the EU directives, aiming at certain climate related goals. These goals however, do not necessarily contribute towards this desired faster economic recovery, since they focus at other aspects, while they necessitate the commitment of considerable capital. Possibly, they could also hinder the primary challenge of the country.

Therefore, it could be interesting to speculate on the possibilities of: i) having two groups of member states which decisions and rules are addressing, and/or ii) member states being able to temporarily suspend their commitments when they have certain challenges, e.g. not put too much focus on GHGs emissions mitigation, in order to boost growth more rapidly. The investigation of related scenarios could potentially provide valuable insights.

Furthermore, the projections made in this study are giving insights about the three factors of the economy investigated here as well as the GDP. Besides these larger aspects of the economic system, it would be useful to make more in-depth sectoral analyses, to investigate which specific parameters can triggers a transition that can bring the desired benefits. This could be done by estimating the value of the in between steps of a longer process. For example, when promoting electric vehicles, a study could exist to examine how much investment would be necessary to achieve a specific future target, and also, how many jobs would be created for the labor of such a transition, or what barriers have to be overcome in order persuade communities to attempt these investments.

Chapter 5

Conclusions

In this final chapter of the thesis, the objective of the work is briefly formulated, the conclusions are summarised and recommendations for future work are suggested.

The thesis had two objectives. The first was to investigate the relationship between useful work and economic growth. The second was to examine whether the faster recovery of the Greek economy is possible, when measures are taken to improve its aggregate exergy efficiency. To do that, the exergy data and economic figures of the country were analyzed and past trends were revealed. The country's exergy analysis of the four main economy sectors was realized with the help of the Useful Exergy Accounting Methodology. Then, two extreme scenarios were created, one pessimistic and one optimistic, which included assumptions for the future development, by 2030, of three factors; labor, capital stock and aggregate exergy efficiency. Estimates of GDP based on these three factors were generated using the economic model of the MEET2030 project.

The exergy research in the main economy sectors up to 2014 showed that, the energy carriers consumed primarily are oil products, which have a share higher than 50%, while second comes electricity, with a share of 25%. The majority of total final exergy is injected to produce mechanical drive, which takes almost half of its share, while next come low temperature processes, with around 25% share. The greatest portion of useful work produced is occupied by mechanical drive, with more than 60% share, and then comes heat, mostly of medium and low temperature, with around 12% share each. The most useful work intensive sub-sectors of economy are those of road transportation, residencies, services, non-ferrous metals and non-metallic minerals industries, and oil refineries.

It was identified that, a relatively stable correlation between useful work and economic growth exists in Greece, considering the last three decades of the examined period. Specifically, the useful work intensity index was estimated around 0.86 MJ/€. However, this intensity does not seem to be the same with other countries' indexes.

From the findings in the UW shares and in the UW intensity, it is shown that the main form of useful work that drives economy seems to be mechanical drive, while second comes heat.

The methodology and the economic model of MEET2030 were applicable for the case of Greece. Two viable scenarios were created for its future development.

It was shown that, the implementation of measures which address the exergy intensive sectors of economy, by improving their exergy efficiencies, appears to have positive influence on the economic growth of Greece. This was enabled through the link of exergy efficiency with total factor productivity.

The progress in exergy efficiency was achieved by two manners i) improving efficiencies in all technologies and ii) transitioning towards more efficient energy carriers. The later refers to a) the switch from conventional combustible fuels to non-conventional heating technologies, such as solar thermal and b) the further electrification of MD. In the case of stronger adjustments, the outcome was better. Namely, in the pessimistic scenario, the improvement in final-to-useful aggregate efficiency was from 20.07% to 22.4%, while in the optimistic scenario the efficiency rose up to almost 25%. These rises in domestic efficiency would also contribute in the common goal of increasing the efficiency in EU level.

The two economic growth projection results differed significantly, substantially creating a range of possible outcomes by the end of the forecasted period. The pessimistic scenario, with annual average growth of 1.2%, led to GDP values comparable to pre-crisis levels. The optimistic one showed growth rates around 2.9% and reached a GDP of about 11% above the 2007 peak. Thus, it can be concluded that making decisions, pushing policies and taking measures inside the spectrums of those in the scenarios, has the potential to bring progress for the economy and the society.

Projections were made for the useful work and final exergy of the country as well, based on the previously found useful work intensity and aggregate exergy efficiency. Both tended to increase, following the GDP development. Yet, final exergy grew slower than useful work and GDP, because of the improvement in exergy efficiency. This decrease in final exergy intensity implies also the reduction of energy needed to generate wealth.

To investigate whether these scenarios are sustainable in respect to the European climate goals, it is suggested to create projections of Greece's energy consumption and GHGs emissions. In case they do not meet the goals of 2030, a third scenario could be formed, which should assume generally more drastic adjustments.

In order to verify that there is a strong constant correlation between useful exergy and economic growth, similar research work could be repeated after one or two decades, for Greece and/or other countries.

More in-depth sectoral analyses could be made in the future to investigate the effect of individual goals and parameters inside the broader transition effort. Examine what their requirements and benefits would be for the society.

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Annex A. Annex

A.1 Annex tables

Annex Table 1: Energy carriers and their products

Energy Carriers	**Products**
Coal and coal products	Hard coal
(includes Peat and peat products)	Brown coal
	Anthracite
	Coking coal
	Other bituminous coal
	Sub-bituminous coal
	Lignite
	Patent fuel
	Coal tar
	BKB
	Gas works gas
	Coke oven gas
	Blast furnace gas
	Other recovered gases
	Peat
	Peat products
Coke	Coke oven coke
	Gas coke
Oil and oil products	Refinery gas
(includes Crude, NGL, refinery feedstocks, oil shale)	Ethane
	Liquefied petroleum gases (LPG)
	Motor gasoline excl. bio
	Aviation gasoline
	Gasoline type jet fuel
	Kerosene type jet fuel excl. bio
	Other kerosene
	Gas/diesel oil excl. bio
	Fuel oil
	Naphtha
	White spirit & SBP
	Lubricants
	Bitumen
	Paraffin waxes
	Petroleum cake
	Non-specified oil products
	Oil shale and oil sands
	Crude/NGL/feedstocks
	Crude oil
	Natural gas liquids
	Refinery feedstocks
	Additives/blending components
	Other hydrocarbons
Natural gas	Natural gas
Biofuels and waste (combustible renewables)	Industrial waste
	Municipal waste (renewable)

	Municipal waste (non-renewable)
	Primary solid biofuels
	Biogases
	Biogasoline
	Biodiesels
	Other liquid biofuels
	Non-specified primary biofuels/waste
	Charcoal
Other non-conventional	Elec/heat output from non-specified manufactured gases
	Heat output from non-specified combustible fuels
	Nuclear
	Hydro
	Solar photovoltaics
	Tide, wave and ocean
	Wind
	Heat pumps
	Electric boilers
	Heat from chemical sources
	Other sources
Electricity	Electricity
CHP and geothermal heat	Heat
	Geothermal
Solar thermal heat	Solar thermal

Annex Table 2: Energy sectors and flows

Sector	**Flow**
Energy industry own use	Coal mines
	Oil and gas extraction
	Blast furnaces
	Gas works
	Gasification plants for biogases
	Coke ovens
	Patent fuel plants
	BKB/peat briquette plants
	Oil refineries
	Coal liquefaction plants
	Liquefaction (LNG)/ regasification plants
	Gas-to-liquid (GTL) plants
	Own use in electricity, CHP and heat plants
	Pumped storage plants
	Nuclear industry
	Charcoal production plants
	Non-specified (energy)
Industry	Iron and steel
	Chemical and petrochemical
	Non-ferrous metals
	Non-metallic minerals
	Transport equipment
	Machinery
	Mining and quarrying
	Food and tobacco
	Paper, pulp and print
	Wood and wood products

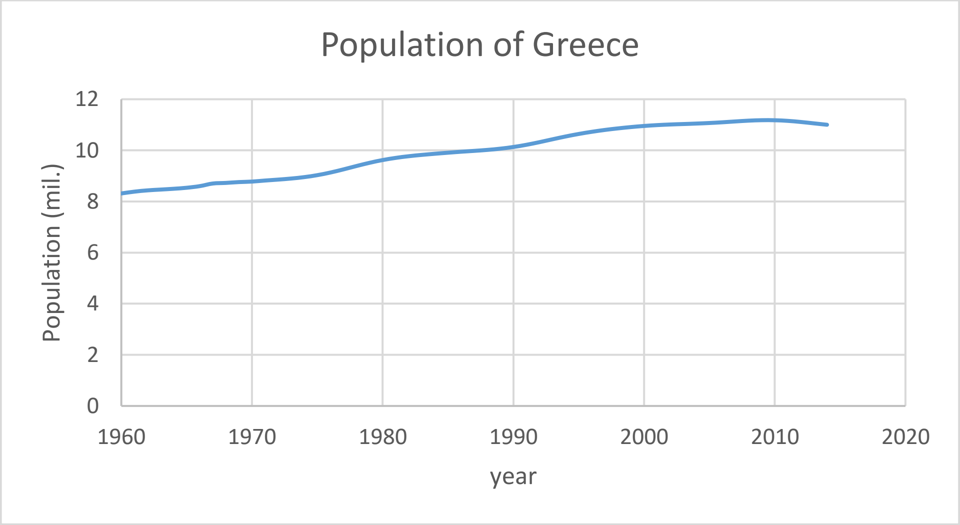
	Construction
	Textile and leather
	Non-specified (industry)
Transport	Domestic aviation
	Road
	Rail
	Pipeline transport
	Domestic aviation
	Non-specified (transport)
Other	Residential
	Commercial and public services
	Agriculture/forestry
	Fishing
	Non-specified (other)

Annex Table 3: Changes of product UW shares in sub-sectors, 2014-2030.

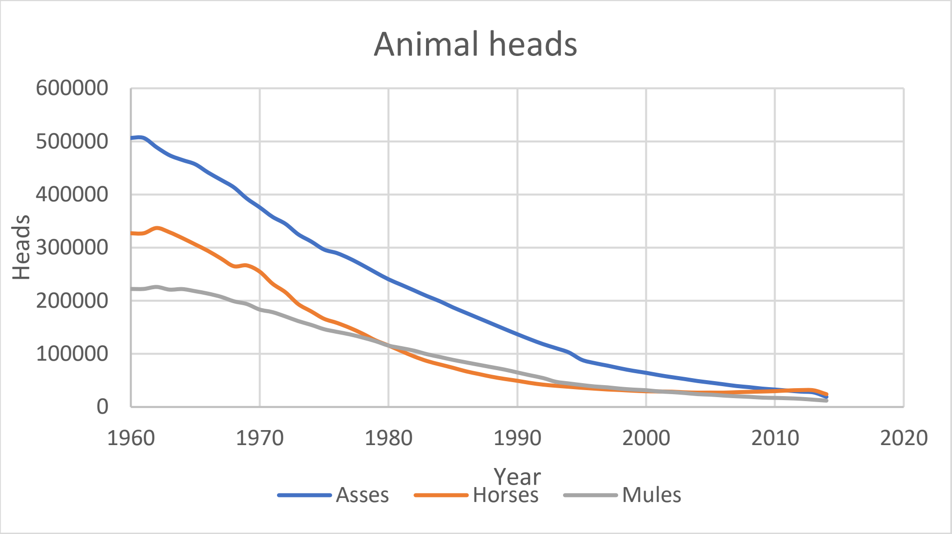
			2014	**BaU - 2030**	**EEE - 2030**
			UW share in sub-sector		
Subs-sector	**Product**	**End-use**	**(%)**	**(%)**	**(%)**
Oil refineries	Refinery gas	Fuel-MTH(150°C)	31.2	26.5	24.5
	Fuel oil	Fuel-MTH(150°C)	33.4	30.4	28.4
	Petroleum coke	Fuel-MTH(150°C)	22.7	22.7	20.7
	Heat	CHP-MTH(150°C)	0.0	7.7	13.7
Non-ferrous metals	Bituminous coal	Fuel-MTH(150°C)	7.4	6.4	5.0
	Lignite	Fuel-MTH(150°C)	1.6	1.0	0.0
	LPG	Fuel-MTH(150°C)	0.2	0.0	0.0
	Fuel oil	Fuel-MTH(150°C)	0.4	0.0	0.0
	Petroleum coke	Fuel-MTH(150°C)	0.1	0.0	0.0
	Heat	CHP-MTH(150°C)	0.0	2.0	5.0
Non-metallic minerals	Bituminous coal	Fuel-HTH(500°C)	14.1	12.9	6.9
	Natural gas	Fuel-HTH(500°C)	5.5	7.0	11.0
	LPG	Fuel-MTH(150°C)	0.3	0.0	0.0
	Gas/diesel oil	Oil-Stationary MD	3.0	2.0	2.0
	Petroleum coke	Fuel-MTH(150°C)	53.2	50.0	45.0
	Other oil products	Fuel-MTH(150°C)	0.4	0.0	0.0
	Prim. sol. biofuels	Fuel-LTH(120°C)	2.2	1.2	0.0
	Biodiesels	Fuel-HTH(500°C)	0.2	0.2	2.2
	Solar thermal	CHP-LTH(120°C)	0.0	1.0	1.2
	Electricity	Electricity-Industry	20.6	21.6	21.6
	Heat	CHP-MTH(150°C)	0.0	4.0	9.9
Food and Tobacco	Natural gas	Fuel-LTH(90°C)	7.6	9.0	11.0
	LPG	Fuel-LTH(90°C)	6.6	4.0	2.0
	Fuel oil	Fuel-LTH(90°C)	7.3	5.5	4.0
	Prim. sol. biofuels	Fuel-LTH(90°C)	11.7	12.86	11.4
	Biogases	Fuel-LTH(90°C)	0.2	1.0	2.0
	Biodiesels	Fuel-LTH(90°C)	0.1	1.0	3.0
Road	LPG	Gasol./LPG vehicles	4.0	4.0	4.0
	Motor gasoline	Gasol./LPG vehicles	48.4	46	40.0
	Gas/diesel oil	Diesel vehicles	43.9	39.9	38.0
	Biogasoline	Gasol./LPG vehicles	0.0	4.0	6.0
	Biodiesels	Diesel vehicles	3.2	4.0	6.0
	Electricity	Electricity-Transports	0.3	2.0	6.0
Rail	Gas/diesel oil	Diesel vehicles	53.5	45.0	37.0
	Biodiesels	Diesel vehicles	3.7	5.0	8.0
	Electricity	Diesel-electric	42.8	50.0	55.0
Domestic Navigation	Gas/diesel oil	Navigation	42.4	42.0	39.0
	Fuel oil	Navigation	57.4	57.0	54.0
	Biodiesels	Navigation	0.21	1.0	2.0
	Heat	Navigation	0.0	0.0	5.0

Residential	Natural gas	Fuel-LTH(50°C)	2.8	4.8	7.3
	LPG	Oil-Stationary MD	6.0	5.0	4.0
	Gas/diesel oil	Fuel-LTH(50°C)	10.5	8.5	6.0
	Prim. sol. biofuels	Fuel-LTH(50°C)	8.6	8.0	5.0
	Charcoal	Fuel-LTH(50°C)	0.5	0.0	0.0
	Solar thermal	CHP-LTH(50°C)	1.2	3.7	8.2
	Electricity	Electricity-Other sect.	69.9	68.9	69.0
	Heat	CHP-LTH(50°C)	0.5	1.1	1.5
Com. & publ. services	Natural gas	Fuel-LTH(50°C)	2.0	1.0	1.0
	LPG	Oil-Stationary MD	3.9	2.6	0.0
	Motor gasoline	Oil-Stationary MD	0.8	0.8	0.0
	Gas/diesel oil	Fuel-LTH(50°C)	0.7	0.6	0.0
	Fuel oil	Fuel-LTH(50°C)	0.1	0.1	0.0
	Petroleum coke	Fuel-LTH(50°C)	0.1	0.0	0.0
	Prim. sol. biofuels	Fuel-LTH(50°C)	0.1	0.0	0.0
	Biogases	Fuel-LTH(50°C)	0.1	0.2	0.0
	Geothermal	CHP-LTH(50°C)	0.1	0.2	1.0
	Solar thermal	CHP-LTH(50°C)	0.1	2.0	5.9
	Electricity	Electricity-Other sect.	92.0	92.0	90.0
	Heat	CHP-LTH(50°C)	0.0	0.6	2.0

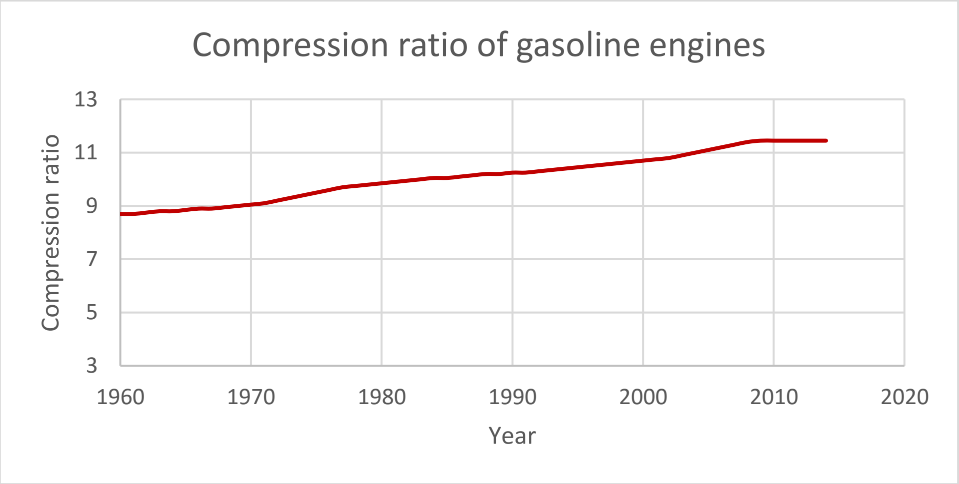
A.2 Annex Figures



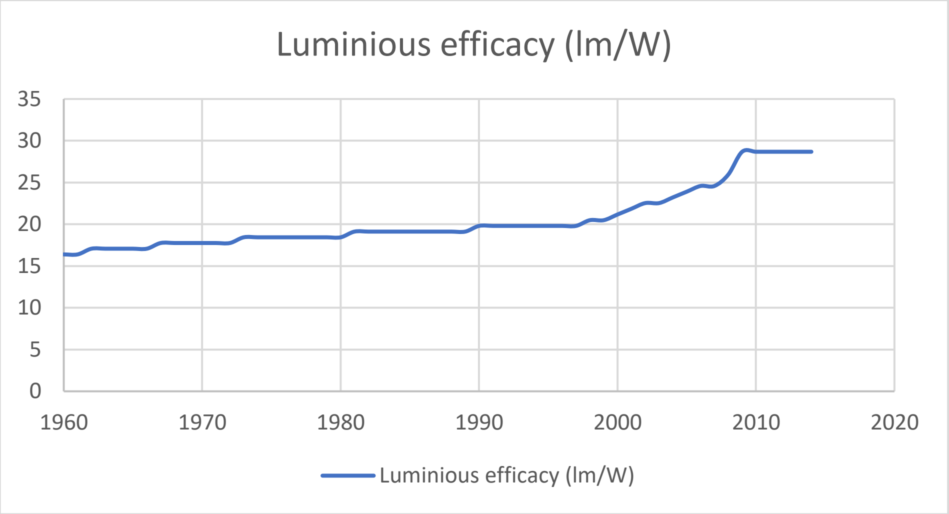
Annex Figure 1: Population of Greece in million inhabitants, 1960-2014 [7].



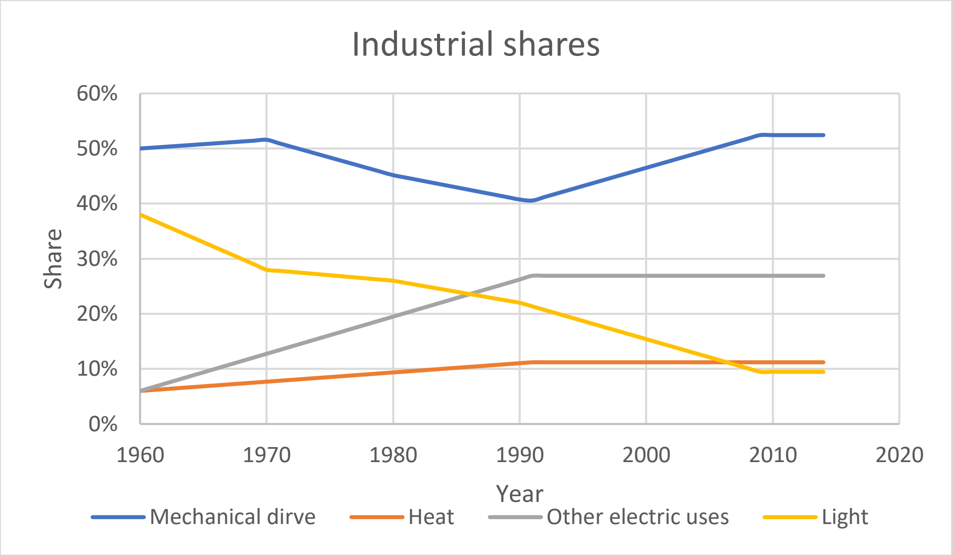
Annex Figure 2: Population of asses, horses and mules in Greece, 1960-2014 [9].



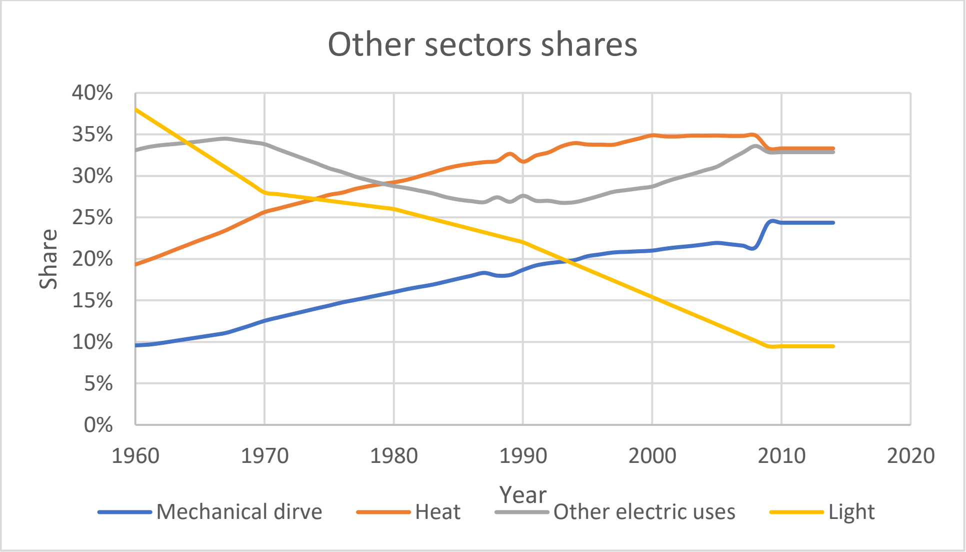
Annex Figure 3: Evolution of compression ratio of standard gasoline engines.



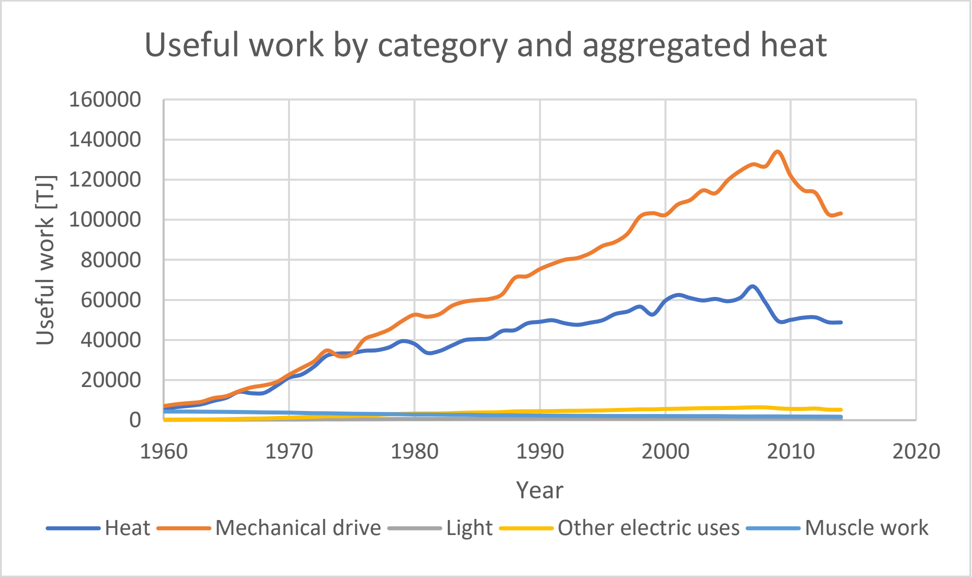
Annex Figure 4: Evolution of the average luminous efficacy [16].



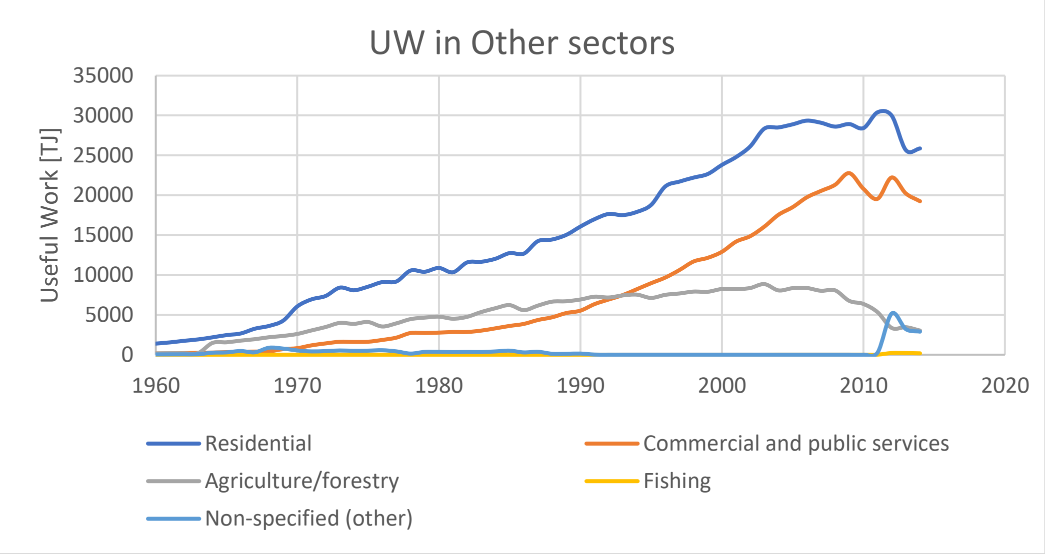
Annex Figure 5: End-use shares of electricity in Industries [3], [4], [24].



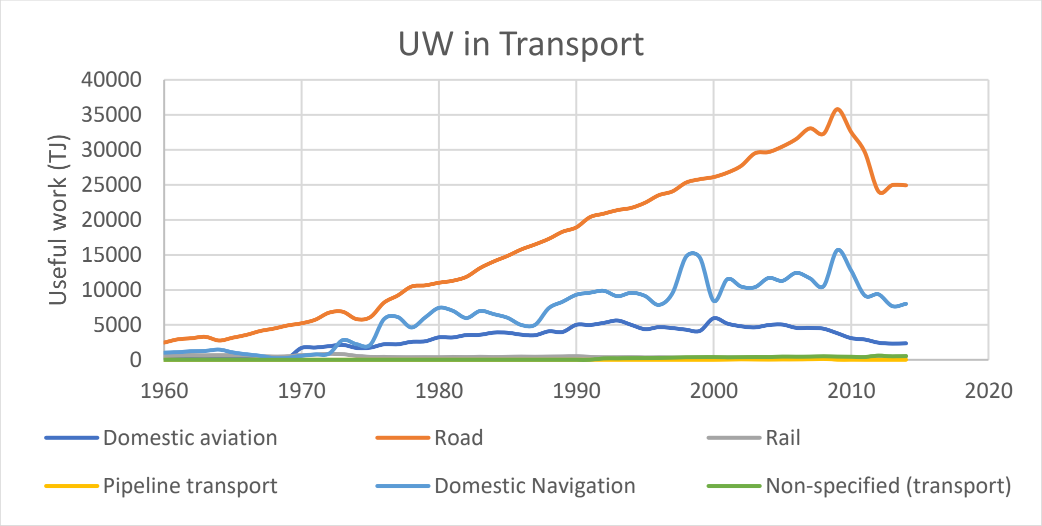
Annex Figure 6: End-use shares of electricity in Other sectors [4], [5], [20].



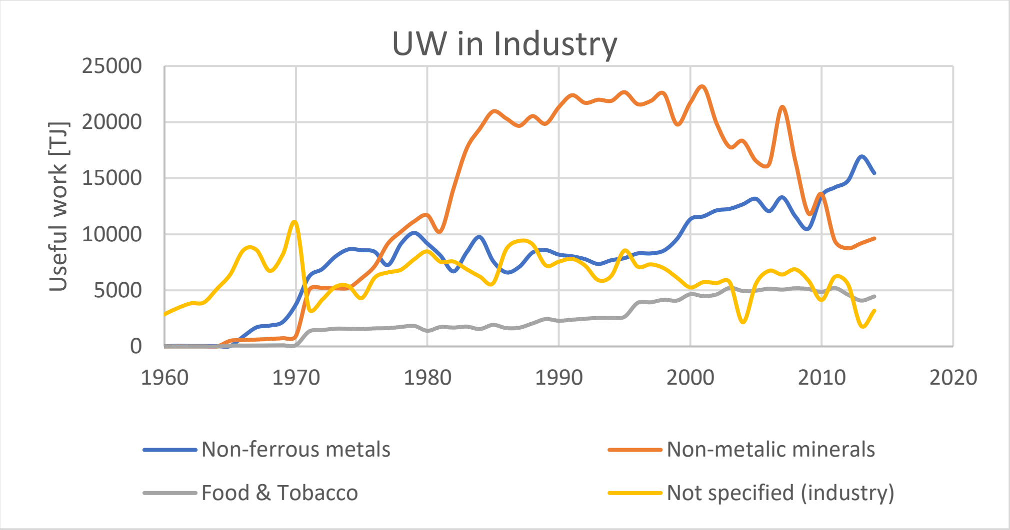
Annex Figure 7: Useful work by category and aggregated heat in Greece, 1960-2014.



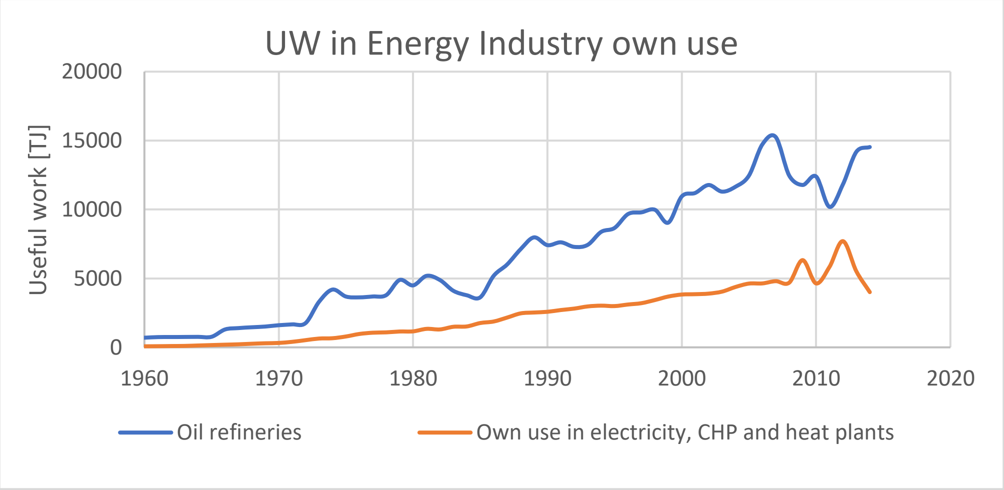
Annex Figure 8: Useful work of sub-sectors in Other sectors in Greece, 1960-2014.



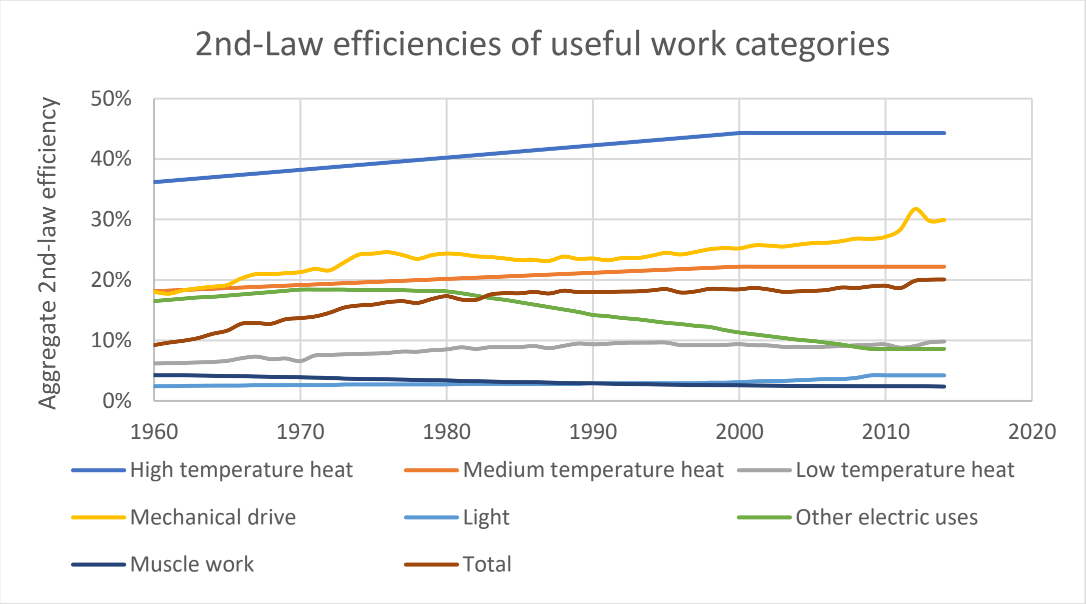
Annex Figure 9: Useful work of sub-sectors in Transport in Greece, 1960-2014.



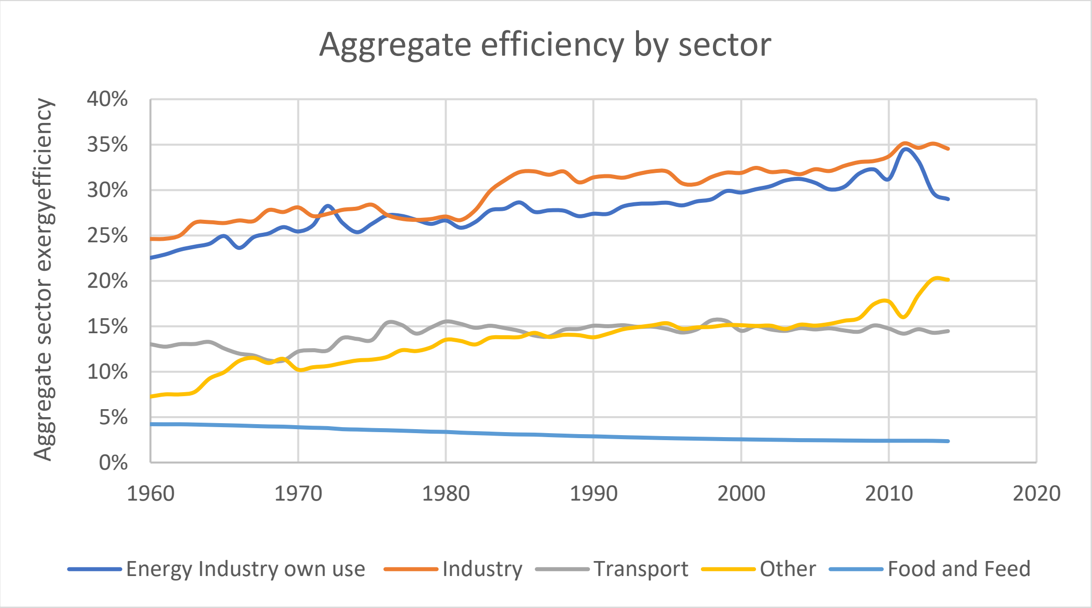
Annex Figure 10: Useful work of sub-sectors in Industry in Greece, 1960-2014.



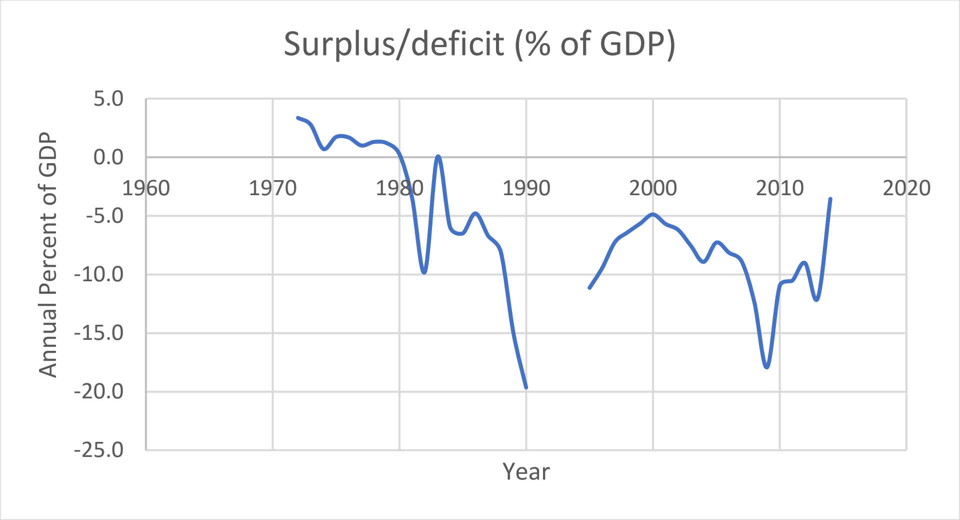
Annex Figure 11: Useful work of sub-sectors in Energy Industry own use in Greece, 1960-2014.



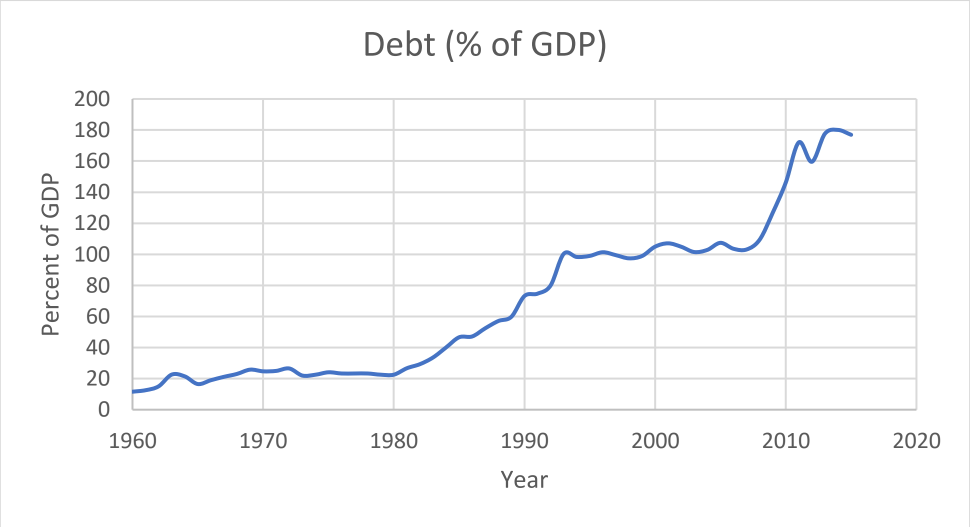
Annex Figure 12: Aggregate second-law efficiencies of useful work categories in Greece, 1960-2014.



Annex Figure 13: Aggregate second-law efficiencies of energy sectors in Greece, 1960-2014.



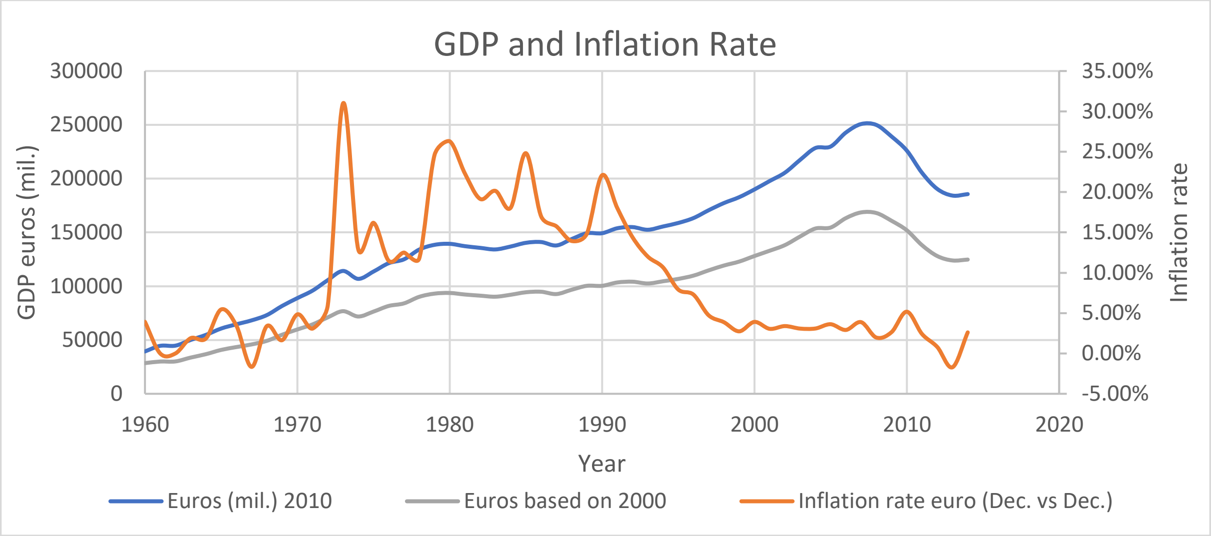
Annex Figure 14: Cash surplus or deficit as percent of GDP for Greece, 1972-2014 [53].



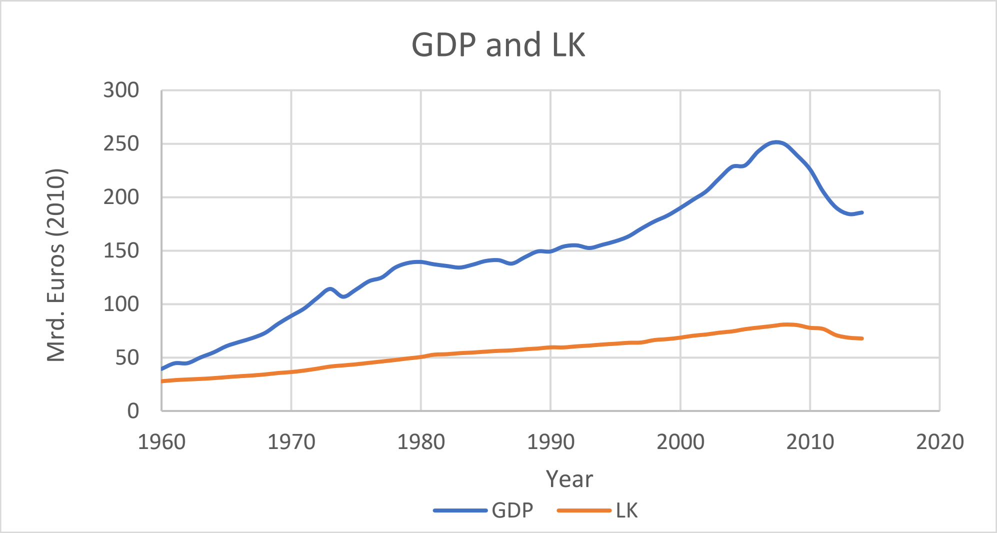
Annex Figure 15: Debt of Greece as percent of GDP, 1960-2015 [54].

In order to convert the monetary values in euros of 2000, eq. (26) was used where in this case year A is 2000, year B is 2010, GDP_y is the gross domestic product of each year i and ir_i is the inflationt rate [55] of each year i. The inflation rates of the time series as well as the GDP of Greece in euros with reference years 2000 and 2010 are displayed in Annex Figure 16.

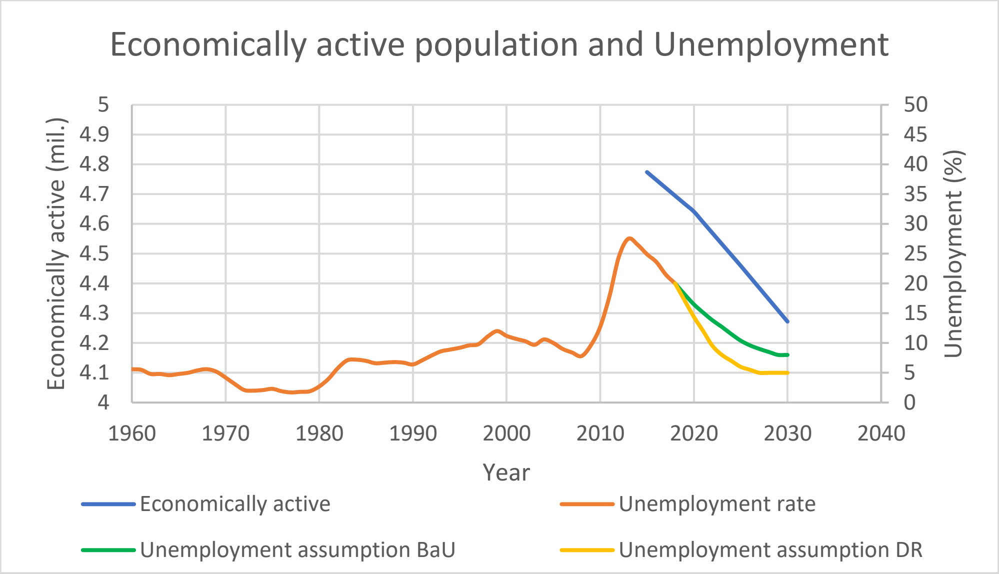
$$GDP_{yA} = GDP_{yB} * \frac{1}{\prod_{i=yA+1}^{yB}(1+ir_i)} \qquad (26)$$



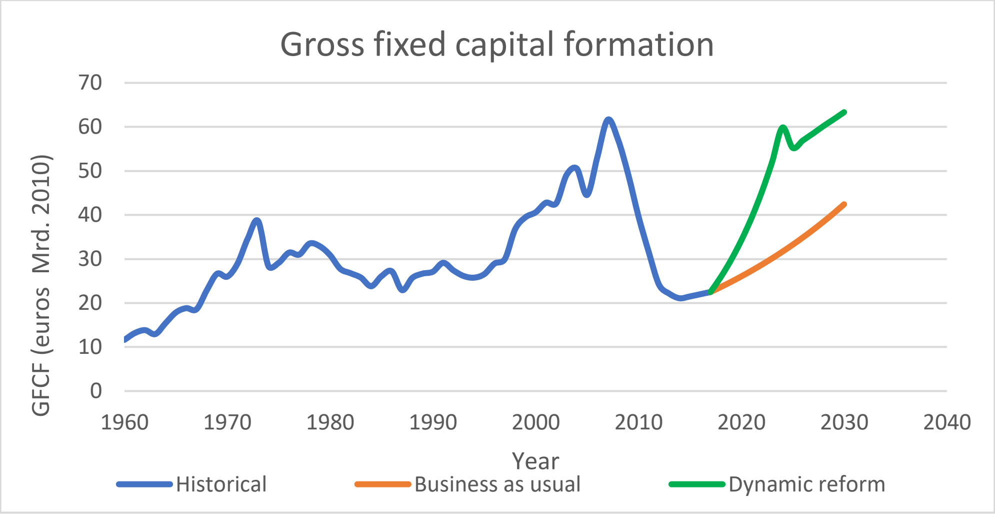
Annex Figure 16: GDP of Greece in 2000 and 2010 euro as reference and inflation rate, 1960-2014.



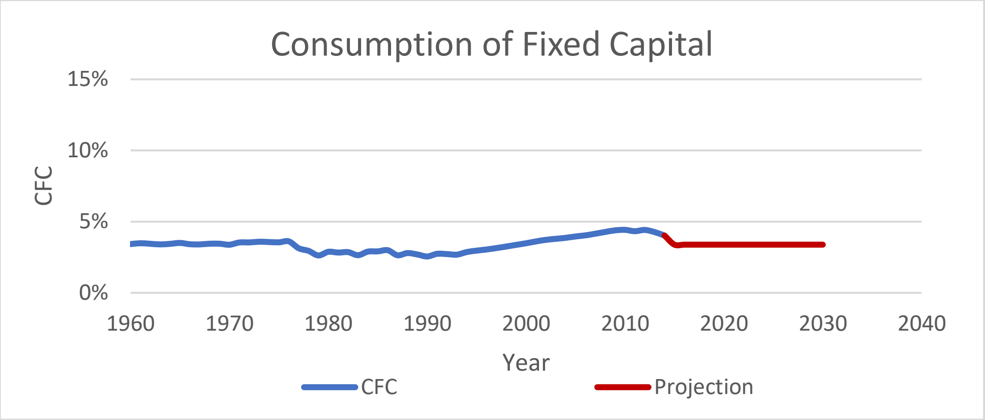
Annex Figure 17: Comparison of GDP with output of only Labor and Capital for Greece, 1960-2014.



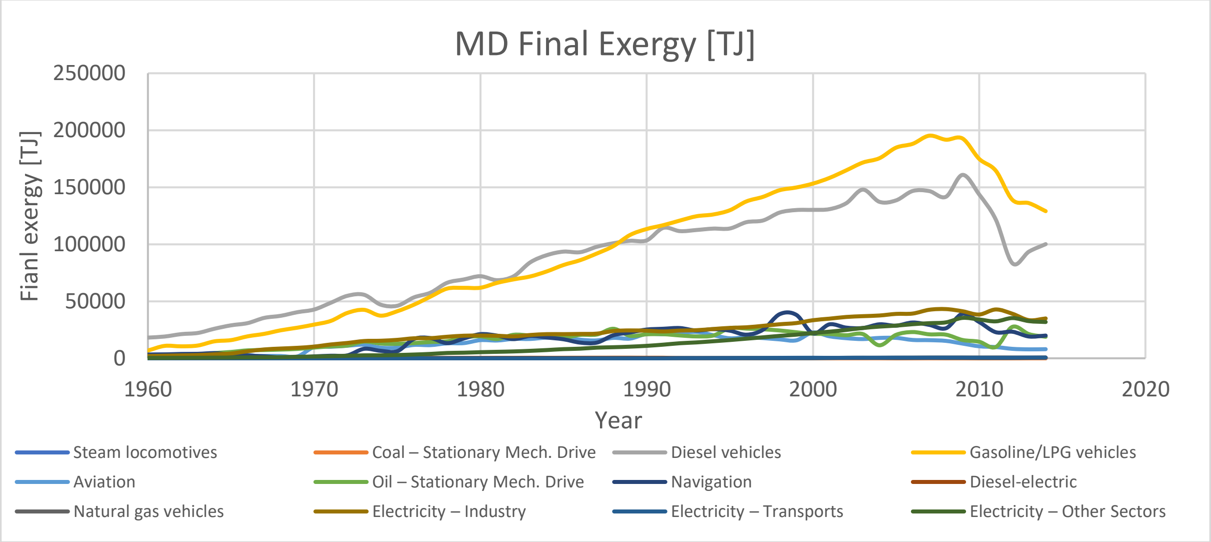
Annex Figure 18: Economically active population projection and unemployment rate in Greece.



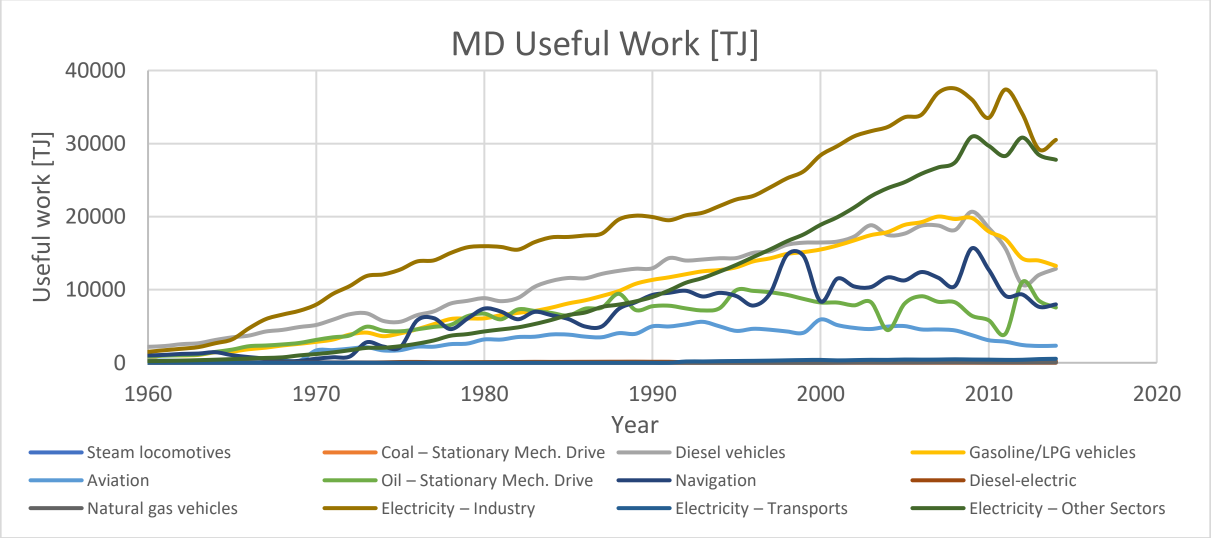
Annex Figure 19: Gross fixed capital formation in Greece from 1960 to 2017 [25] and future scenarios 2018-2030.



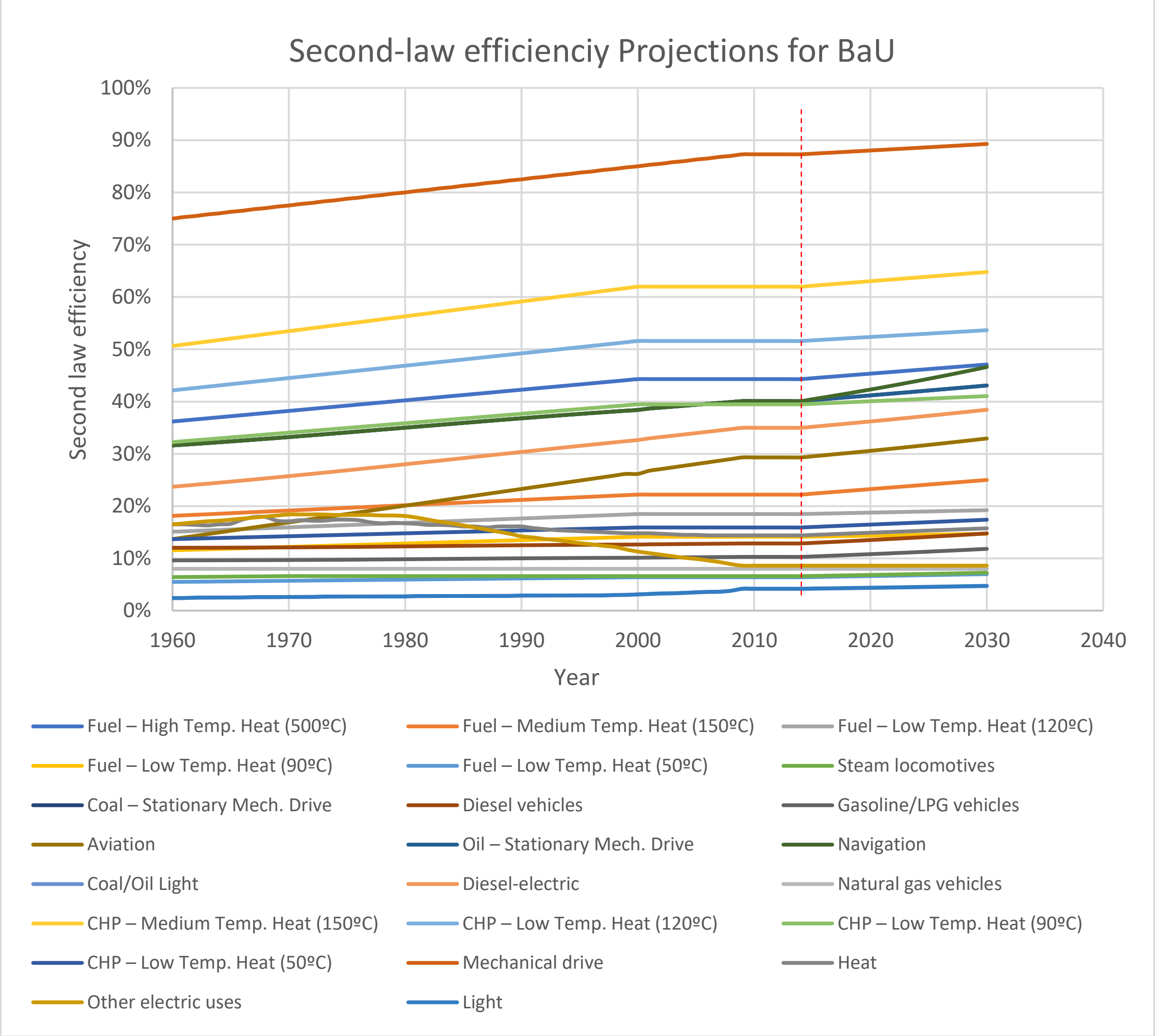
Annex Figure 20: Historical consumption of Fixed Capital in Greece and future projection, 1960-2030.



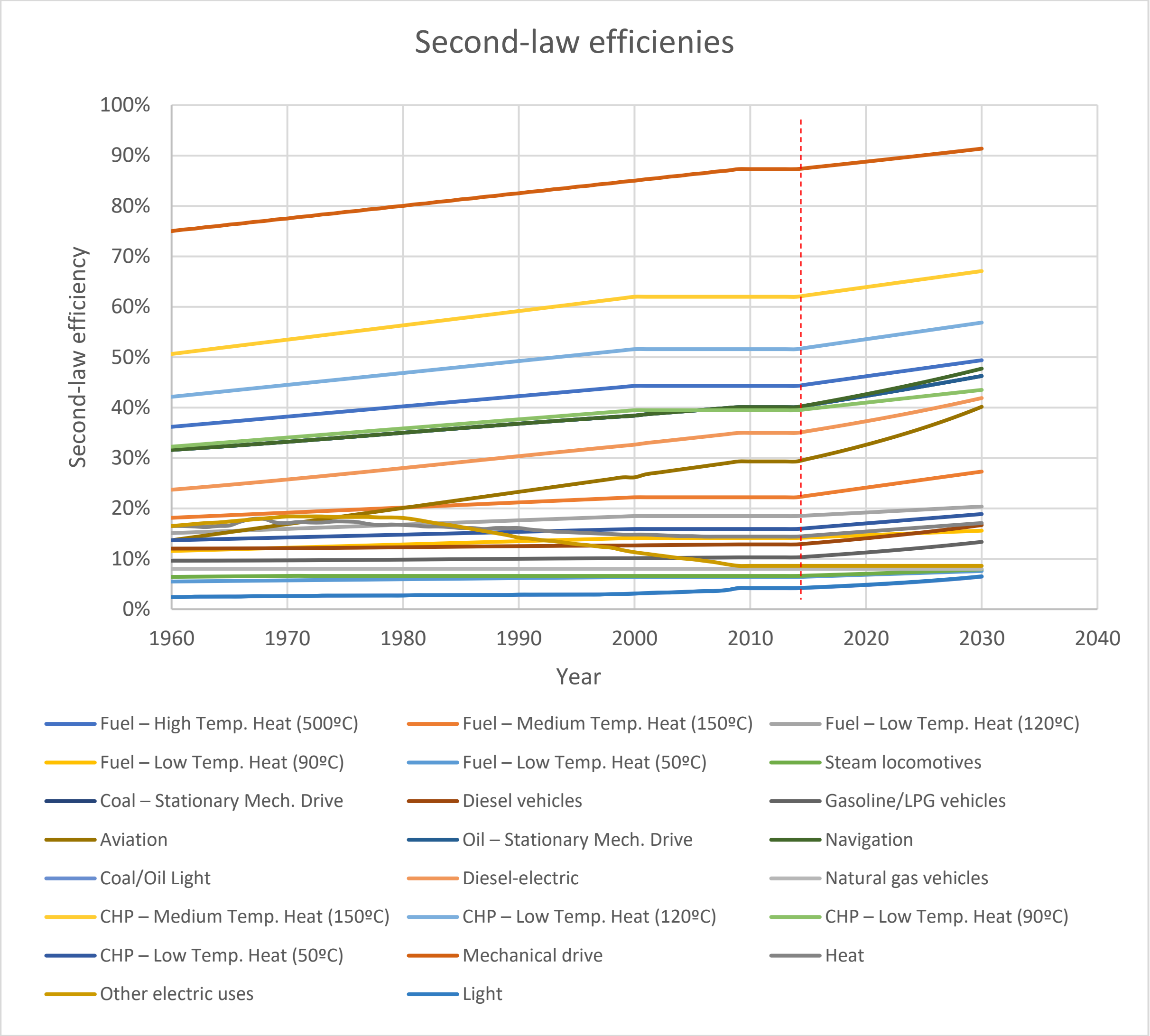
Annex Figure 21: Final exergy in different mechanical drive end uses, 1960-2014.



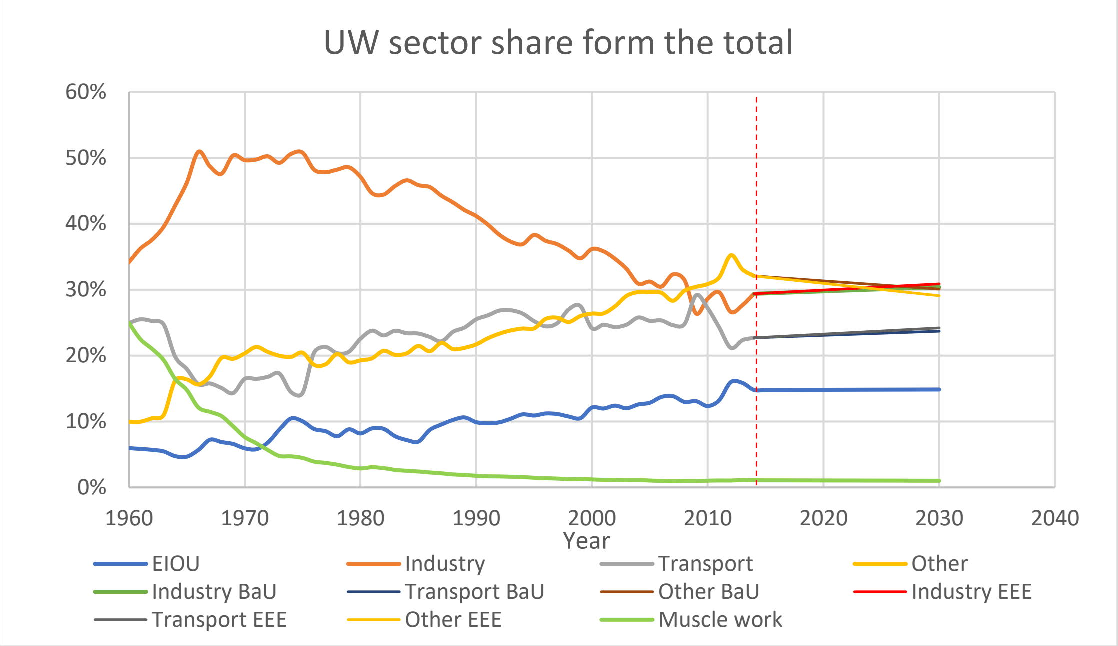
Annex Figure 22: Useful work in different mechanical drive end uses, 1960-2014.



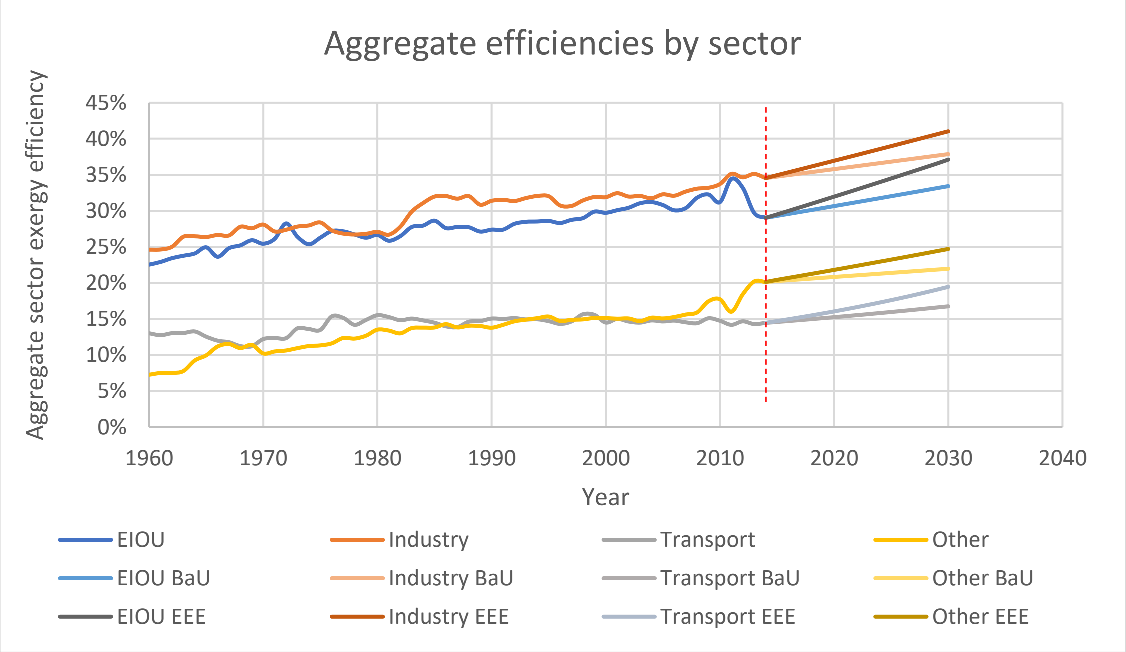
Annex Figure 23: Second-law efficiency assumptions of all end-uses for BaU, 2015-2030.



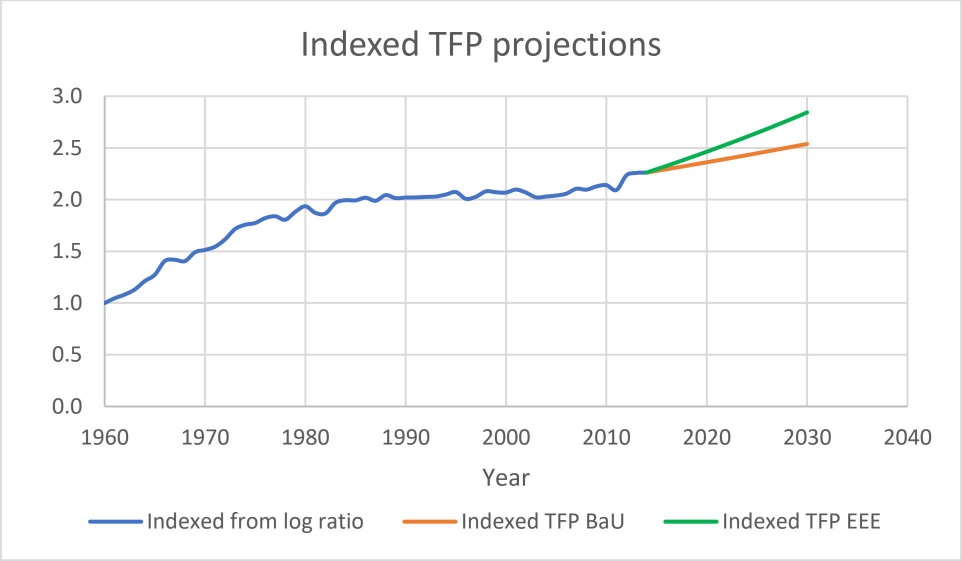
Annex Figure 24: Second-law efficiency assumptions of all end-uses for EEE, 2015-2030.



Annex Figure 25: Shares of economy sectors of Greece and future scenario development, 2015-2030.



Annex Figure 26: Aggregate exergy efficiency by sector in Greece and future scenarios, 2015-2030.



Annex Figure 27: Indexed TFP projections for the two efficiency scenarios of Greece, 2015-2030.